Volume 53 August 1958 Number 5

Economic Geology

and the

Bulletin of the Society of Economic Geologists

CONTENTS

Coal Geology and the Coal Industry ..... *Gilbert H. Cady* 511

The Chemical Environment of Pitchblende ..... *Leo J. Miller* 521

The Geology and Metamorphism of the Nairne Pyritic Formation, A Sedimentary Sulfide Deposit in South Australia ..... *Brian J. Skinner* 546

Rank of Coal and Metamorphic Grade of Rocks of the Narragansett Basin of Rhode Island ..... *Alonzo W. Quinn and Herbert D. Glass* 563

Manganese Ores from the Kuruman District, Cape Province, South Africa ..... *J. J. Frankel* 577

Sulfur Isotopes and the Origin of Sandstone-Type Uranium Deposits ..... *M. L. Jensen* 598

Scientific Communications:

Solubility Product and Ore Precipitation ..... *Norman Street* 617

Localization of Ore Districts ..... *H. J. Ward* 618

Discussions:

On the Occurrence of Uranium in Ancient Conglomerates ..... *Paul Ramdohr* 620

John A. S. Adams and Richard Pfiler 621

Ore Genesis—The Source Bed Concept ..... *Kenneth A. Phillips* 622

Martin D. Kierans 623

Reviews:

An Introduction to Graphic Solutions of Geologic Structures—Laboratory Exercises and Problems (A. N. MacIntosh) ..... *Alan T. Broderick* 626

The Future Supply of Oil and Gas (B. C. Netschert) 626

The Atomic Age and Our Biological Future (H. V. Brønsted) 627

Engineering Geology Case Histories No. 2 (P. D. Trask, Ed.) 627

Principles of Geodynamics (A. E. Scheidegger) 628

Geologie und Bodenschatze Afrikas (E. Krenkel) 628

The Mineragraphy of the Radium Hill Uranium Deposits and the Delineation of the Whip and Geiger Lodes (R. F. LaGanza) 629

Introduction to Geology (H. E. Brown, V. E. Monett and J. W. Stovall) 629

Books Received ..... *James M. Allen* 630

Scientific Notes and News 636

PUBLISHED SEMI-QUARTERLY

Six Dollars Fifty Cents a Year, One Dollar Twenty-five Cents a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

Issued Semi-Quarterly and sent to subscribers on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15.

Manuscripts for publication should be sent to the Editor, **ALAN M. BATEMAN, at Yale University, Yale Station, New Haven, Conn.** It is requested that contributors exercise care in writing *scientific* and *proper names*. References to other publications should be in accordance with the forms used in the pages of this journal. The manuscript should be typewritten with double space lines and must be preceded by *a brief abstract*. Galley proof will be sent authors only where a request to this effect accompanies the manuscript, or when, in the editor's opinion, the subject matter is such as will require correction by the author.

Reviews should conform to the journal usage. Review Committee: The Editor, C. H. Behre, L. C. Graton, J. T. Singewald, Jr., J. Gilluly, A. F. Buddington, W. H. Newhouse.

Books and Pamphlets for review should be sent to the Editor.

Reprints. Contributors desiring reprints of their papers may obtain them by filling out the order slip which will be attached to the galley proof when it is sent to the author. Provided the order slip is received by the editor, *with the return of the proof*, 50 reprints without covers will be furnished without charge. Reprints of discussions and informal communications are not furnished free of charge except when they exceed four pages in length when 50 will be supplied without charge. Reprints of reviews are not supplied. Additional reprints will be furnished at approximately the rates given in the table below (effective with No. 5) when ordered *in advance of publication*. The rates apply only to plain text, with line engravings. Papers containing folded maps or plates will be more expensive.

The following rates do not include free carriage. *Postage or express must be paid by the author.*

	4 pp. 1–4	8 pp. 5–8	12 pp. 9–12	16 pp. 13–16	20 pp. 17–20	24 pp. 21–24	28 pp. 25–28	32 pp. 29–32	Covers
50 copies.....	$4.20	$6.65	$10.40	$10.85	$14.15	$16.25	$18.70	$19.95	$5.75
100 "	5.00	7.95	12.00	13.30	17.00	19.95	23.30	25.00	7.80
Additional copies per C.	1.70	2.55	4.20	5.00	5.85	7.50	9.15	10.00	3.75

For 500 copies deduct 5%; for 1000 copies or more deduct 10%. For more than 32 pages add cost per schedule to make total. Example: For 44 pages add cost for 32 pages and 12 pages. The 50 copy price is the minimum charge.

Covers: Standard covers are of the same style of type and paper as the cover of the journal, and bear the title of the article and name of its author. Special printing on cover is charged for at the cost of composition.

Plates are $4.20 for the first 50 if printed on one side, and $3.15 per "C" for additional's; printed on both sides, $6.30 for the first 50, and $4.70 per "C" for additional's.

Collotype plates are 8 cents each for each additional reprint over the 50 copies furnished free. Example: An extra 50 reprints containing one collotype plate would cost $4.00; 2 collotype plates, $8.00.

Note: For any reprints requiring additional composition or changes, either in text or cover, an extra charge will be made.

The retail prices of single reprints when available from the office of the Business Manager are as follows:

1–4 pp. 15c	5–8 pp. 20c	9–12 pp. 25c	13–20 pp. 30c	21–28 pp. 35c
29–36 pp. 40c	37–44 pp. 45c	45–52 pp. 50c	53–60 pp. 55c	61–68 pp. 60c

Subscriptions. The price of the journal to subscribers in the United States and its dependencies is $1.25 for a single copy, or $6.50 a year for eight numbers effective July 1, 1953. To subscribers in Canada, Cuba, Mexico, Spain, and countries in Central and South America, except Dutch and French Guiana, the annual rate is $6.80; to other countries, $7.25.

Forwarding. Subscribers wishing their journal to be forwarded to a new address should leave postage for that purpose with the Postmaster at their old address.

Missing numbers will be replaced without charge if claim is made within four weeks after the date of issue of the following number, provided that the neglect to receive them is not due to neglect to arrange for their forwarding.

Remittances should be made payable to the **ECONOMIC GEOLOGY PUBLISHING COMPANY,** and should be mailed to **M. M. LEIGHTON,** Business Manager, Urbana, Illinois, to whom also all **Business Communications** should be addressed.

Foreign Agents. The Technical Bookshop, Salisbury House, London Wall, London E. C. 2, England, British Agents.

Indexed in the Industrial Arts Series.

LANCASTER PRESS, INC., LANCASTER, PA.

5, 1879

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

EDITOR: ALAN MARA BATEMAN
Yale University, New Haven, Connecticut

BUSINESS EDITOR: MORRIS M. LEIGHTON
Illinois Geological Survey, Urbana, Illinois

ASSISTANT EDITORS

H. E. MCKINSTRY, *Harvard University*
M. LEROY JENSEN, *Yale University*
JOE W. PEOPLES, *Wesleyan University*
J. D. BATEMAN, *Toronto, Ont.*
R. H. JAHNS, *California Institute of Technology, Pasadena*

ASSOCIATE EDITORS

D. F. HEWETT
U. S. Geological Survey, Menlo Park, Calif.

A. I. LEVORSEN
Tulsa, Okla.

B. S. BUTLER
Univ. of Arizona, Tucson, Ariz.

W. E. WRATHER
Washington, D. C.

A. N. SAYRE
U. S. Geological Survey, Washington, D. C.

L. C. GRATON
Orange, Connecticut

E. S. MOORE
Univ. of Toronto, Toronto, Can.

GEORGE W. MOREY
U. S. Geological Survey, Washington, D. C.

PER GEIJER
Djursholm, Sweden

P. F. FOURMARIER
Liège University, Liège, Belgium

M. S. KRISHNAN
Ministry Natural Resources and Scientific Research, New Delhi, India

T. W GEVERS
University of the Witwatersrand, Johannesburg, S. Africa

C. F. DAVIDSON
St. Andrews Univ., Fife, Scotland

J. A. BROGGI
Instituto Geologica, Lima, Peru

TAKEO WATANABE
University of Tokyo, Tokyo, Japan

KONRAD B. KRAUSKOPF
Stanford University, California

A SEMI-QUARTERLY JOURNAL PUBLISHED BY
THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Indexed in the Industrial Arts Series.

LANCASTER PRESS, INC., LANCASTER, PA.

SOCIETY OF ECONOMIC GEOLOGISTS

THE PUBLICATIONS OF WHICH CONSTITUTE
A PART OF THIS JOURNAL

OFFICERS FOR 1958

GEORGE M. SCHWARTZ, *President*

HUGH M. ROBERTS, *Vice President*

HAROLD M. BANNERMAN, *Secretary*, U. S. Geological Survey, Washington 25, D. C.

JOSEPH T. SINGEWALD, JR., *Treasurer*, Johns Hopkins University, Baltimore 18, Maryland

Councilors

1958	*1959*	*1960*
F. S. TURNEAURE	JAMES BOYD	PHILIP W. CHASE
DONALD M. FRASER	DUNCAN R. DERRY	ROBERT M. GARRELS
CHARLES MEYER	W. H. CALLAHAN	EDWARD H. WISSER

Regional Vice Presidents

ARNOLD E. WATERS, JR., Africa.....PER A. GEIJER, Europe
M. S. KRISHNAN, Asia.....E. C. HARDER, North America
CHARLES E. MARSHALL, Australia.....H. C. ALVES DE SOUZA, South America

Executive Committee

GEORGE M. SCHWARTZ, *Chmn.* GILBERT H. CADY JOSEPH L. GILLSON
HUGH M. ROBERTS JOSEPH T. SINGEWALD, JR. HAROLD M. BANNERMAN

President's appointments to Committees for 1958–59

Finance Committee

JOSEPH T. SINGEWALD, JR., *Chairman* OLAF N. ROVE DONALD M. FRASER

Program Committee

JOHN H. MELVIN, *Chairman* M. L. JENSEN J. S. STEVENSON
ROBERT M. GROGAN PETER JORALEMON HAROLD M. BANNERMAN, *Ex-officio*
CARL TOLMAN

Committee on Publications

R. M. FOOSE, *Chairman* JOHN H. FFOLLIOTT ELDRED D. WILSON

Nominating Committee

CHARLES MEYER, *Chairman* JAMES M. HARRISON PHILIP J. SHENON

Admissions Committee

F. S. TURNEAURE, *Chairman* JOHN W. AMBROSE CARL E. DUTTON
FRANK C. FOLEY PATRICK M. HURLEY

Auditing Committee

FRANCIS G. WELLS, *Chairman* A. NELSON SAYRE

Coal Research Committee

ROBERT M. KOSANKE, *Chairman* IRVING M. BREGER
CHARLES E. WIER JAMES M. SCHOPF

Representative to AAAS.....W. H. BRADLEY
Representative to National Research Council.....WALTER S. WHITE

ORDER BLANK

FIFTIETH ANNIVERSARY VOLUME
ECONOMIC GEOLOGY
1905-1955

(See page ii)

☐ Enclosed is $..... ☐ Enter my order and send bill

☐ Price to Subscribers $6.00

(including Members, Non-Member Journal Subscribers, and Students whether subscribers or not)

☐ Price to Non-Subscribers to Journal $8.00

To Economic Geology Publishing Company
105 Natural Resources Building
Urbana, Illinois

Mail above copy as checked to:

Name

Street Address

City State Country

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. 53 AUGUST, 1958 NO. 5

COAL GEOLOGY AND THE COAL INDUSTRY[1]

GILBERT H. CADY

ABSTRACT

The more important changes in the American coal industry during the past fifty years have been brought about through the increasing reliance upon mechanization, automation, and management. The changes have been made possible mainly by industrial research, experimentation, and testing, particularly in the fields of mechanical engineering, preparation, and utilization, and by concentration of management. Paralleling such investigations, particularly in government laboratories and geological surveys, have been investigations that concern the mapping and evaluation of resources, on the one hand, and those that concern the basic physical constitution of coal, on the other. The growing pressure being exerted on the already occupied coal reserves, particularly in the eastern part of the country, makes of constantly increasing importance a knowledge of the remaining resources. The increasing use of mechanical methods of mining, accompanied by the increasing production of finer and finer sizes and the attendant increase in mineral impurities in such coal, makes automatic cleaning increasingly essential. It is obvious that these two tendencies approach a condition of diminishing return in terms of ash reduction alone. In the petrographic heterogeneity of coal established by coal petrology, there resides the possibility of more discriminating refinement in preparation than has yet been achieved, particularly with the lower rank bituminous coals. Thus both the study of coal resources and of coal petrology may be rightly included in the general field of applied or economic geology.

I ASSUME that the Society has honored me with election to my present office mainly as a representative of that relatively small but virile group of the Society designated as the coal geologists or coal geochemists. Although this group may be small it represents the geological phase of one of the most important of our mineral resources. It is appropriate to emphasize the great importance of this resource, not only in contributing to our physical comfort

[1] Presidential Address, presented at the Annual Meeting of the Society of Economic Geologists, November 6, 1957.

and well being but also in supporting many of the activities of modern civilization that provide occasion for the services of a much larger group of economic geologists concerned with the discovery, mapping, and development of metallic and industrial minerals.

From time to time, therefore, some statement is desirable in explanation of the relationship and importance of coal geology to the coal industry, since coal geologists do not appear to have such an opportunity more than about once in a decade. It was nearly 10 years ago that Dr. Ashley presented the last Presidential Address of a coal geologist.

Such a statement may also serve to provide the membership with a somewhat better understanding of the nature and scope of coal geology and to strengthen any wavering confidence in the wisdom of the selection of such a branch of geology, which seems so little esteemed in the academic field, for life-time professional activity. Coal geologists are rarely, if ever, the direct product of academic training. The decision to enter this field of geology is usually the result of chance experience during the first years of field training. Why this decision is ever made is considerable of a mystery, but that it sometimes happens we have tangible evidence. Certainly there is no well laid out path into the profession. To the individual who has made this decision may I take occasion to point to the Coal Group (GSA), a child of our own Society, as an organization that will offer encouragement and support for those entering this branch of geological science.

In the ensuing discussion I will first point out the general nature of the important changes that have taken place in the American bituminous coal industry during the past fifty years, as indicated by statistical data obtained from the government publications and a booklet published by the National Coal Association (NCA) in 1956 entitled "Bituminous Coal Trends." I do this because the nature of these changes has a direct bearing on the importance of coal geology and the nature of its applications particularly for the future.

This statement will be followed by a consideration of the character of the research activities whereby the changes have been achieved and the general position of geological research among these activities. This relates particularly to the two fields of coal resources investigations and coal petrology, which are of most immediate importance to the coal industry.

CHANGES IN THE BITUMINOUS COAL INDUSTRY SINCE 1905

The production of bituminous coal and lignite in the United States has increased from about 315 million tons in 1905 to 464 million tons in 1955, or about 50 percent above the 1905 production, with a maximum annual production in 1947 of over 630 million tons. Anthracite during the same fifty years declined from 78 to 44 million tons.

There have been many other important changes: the average price of bituminous coal has risen, but discontinuously, from $1.06 in 1905 to $4.49 in 1955, that is over $3.00 per ton. This is about twice the general increase in commodity prices since 1905, but only partly reflects the increase in miners' wages, which have increased in the order of four times.

The man-power required to produce the coal, however, has declined from 460,909 employees in 1905 to 225,093 in 1955. Most of this decline has taken place since 1950 when there were still 415,000 employees. Thus the number of employees has declined nearly 50 percent in the last 5 years.

There was essentially no mechanical mining before as late as 1923 (0.3 percent), since which time it has increased until now 85.5 percent of the coal is machine mined. Strip mining which started in 1915 with 0.6 percent of the total coal mined has increased to about 25 percent by 1955. The effect of this and other mechanization has been an increase in per day production of the individual miner from 3.4 tons per man day in 1905 to three times that amount (9.84 tons) by 1955.

Parallel changes have taken place in the markets. In 1905 bituminous coal and lignite represented 70.1 percent of the energy produced from fuels plus water power (NCA, p. 26); anthracite 18.4 percent; petroleum 4.7 percent; gas 3.2 percent; and water power 3.2 percent. In 1955 the corresponding figures were bituminous coal and lignite 31.6 percent; anthracite 1.7 percent; petroleum 37 percent; natural gas 26 percent; and water power 3.7 percent.

The change in the pattern of coal utilization has been equally remarkable, as may be seen by comparing figures for as late as 1933 with those for 1955 (NCA). The use of coal by the electric power utilities has increased from 27 to nearly 113 million tons, in spite of the fact that a ton of coal in 1955 produced more than 3 times the electric energy as the same weight in 1920 (3 pounds per KWH in 1920—0.99 pounds per KWH in 1954). The use of bituminous coal by the railroads has declined from a high of 132 million tons in 1945 to only 27 million tons in 1955 (NCA, p. 39); the use of bituminous coal in by-product coke ovens has increased from 38 to more than 104 million tons during the same period. Retail deliveries declined from a maximum of 125 million tons (1944) to less than half that amount (61 million tons) in 1955. These data represent the greatest changes and the largest classes of users in the market. The railroads and domestic markets have suffered the greatest declines because of the increase in the use of fuel oil by the railroads and of fuel oil and natural gas by the householder.

Industrial utilization has not changed a great deal, so that the chief reliance of the coal mining industry now rests upon the utilities and general industrial utilization, particularly the steel industry. This change in the character of the market has been accompanied and to a large extent has been made possible by, and been responsible for, important changes in coal mining and coal preparation procedures. Thus, nearly five times as much coal was crushed to fine size, or originally produced in fine sizes, in 1955 as in 1940 (161 compared with 35 million tons). Furthermore, a good deal of the coal crushed at the mines is further reduced in size at the place of utilization.

This increase in the use and production of coal in fine sizes has been accompanied by a number of parallel changes in mining and preparation operations. Thus only 5.3 percent of the coal produced in 1927 was mechanically cleaned; this percentage had increased to 58.7 percent in 1955. Largely because of the decrease in the importance of railroad and domestic coal, together

with the increase in the use of stokers in various types of installations, the production of lump coal has largely ceased.

Likewise, there has been a great expansion in the use of mechanical methods of mining. For the present purpose it is unimportant which was cause and which effect, but certainly unless combustion engineers had demonstrated the advantages of burning coal in powdered form, the modern types of mining machines could scarcely have acquired their present importance.

Since 1905 the amount of coal cut by machines has increased from 32.8 to 88.1 percent, and that mechanically loaded from 0.3 percent in 1923 to 85.4 percent in 1955. The "continuous miners" were introduced between 1945 and 1950. By 1950 there were 3,143 such machines reported in operation, and, by 1955, 11,830 such machines produced about 8 percent of the bituminous coal (7,460,204 tons). Auger mining has also become feasible with the increased demand for fine coal, and more than 6 million tons of coal were produced by this method in 1955.

Summarizing these data, and adding a few other points, the following outstanding trends of the coal industry during the past fifty years are apparent: a great decline in the number of mines and mining companies; a great decrease in the number of employees; a large increase in the production per man-day; a considerable increase in the amount of bituminous coal and lignite produced; extensive mechanization of the mining operations both above and below ground; great advances in the means and methods of transportation of the coal from the face to the preparation plant; and a great increase in the production of fine coal which is usually accompanied by an increase in the mineral matter content of the mechanically produced coal, making necessary a large increase in the amount of coal mechanically cleaned.

Thus the bituminous coal industry, like many other industries, particularly within the past 10 years has placed increasing emphasis upon mechanization, automation, and management. The trend has been stimulated by the competitive necessity of keeping the price of coal down to where it can successfully compete with other sources of energy, in spite of the constantly increasing cost of labor and equipment. The general result has been to eliminate mining practiced as an art and establish it as an engineering and mechanical process. The outstanding change has been the reduction in the size of the coal as prepared for sale and use.

RESEARCH ACTIVITIES

These changes in the methods of mining, preparation, and utilization of coal have not been spontaneous, or simply a matter of growth. They are interrelated, and the particular type of change that has taken place and the equipment and processes that have been adopted have resulted from changes in the utilization practices, from exploratory and experimental testing, conventional promotion, and from experience gained by trial and error. Thus the loss of markets for lump coal and the parallel enlargement of the small coal market was a fortuitous but more or less unforeseen combination of circumstances greatly to the advantage of automatic mining, loading, and trans-

portation machinery that handled small size coal most advantageously, and made necessary greater dependence upon cleaning process for the production of low ash and low sulfur coal.

All such exploratory and testing operations in mining, preparation, and various forms of utilization fall into the category of research in the eyes of management as represented by such groups as the National Coal Association, various operators' associations and Coal Mining Institutes scattered throughout the country.

The coal mining industry has, of course, been most acutely conscious of the problems that concern coal production and coal utilization, yet it has not been unaware of the importance of an understanding of the fundamental facts in regard to coal occurrence and availability and in regard to the physical and chemical nature of the coal itself.

The coal industry is well aware of the fact that it is an extractive industry and that it must be ready to substitute new supplies of coal for those being lost by mining, with the hope that the quality and availability of the new supplies will be as good or better than those lost by extraction. Likewise, although the interest is more or less incidental, there is an undercurrent of interest in the fundamental character and composition of coal because of a realization of its complexity and its inherent capacity of springing surprises in the way of methods of utilization upon the industry.

TABLE 1

SUMMARY OF COAL RESEARCH BY TYPE OF STUDY 1955*

	Expenditure		Man power	
	Dollars	Percent	Number	Percent
Coal resources	1,478,600	8.5	187	19.8
Mining	3,038,700	17.5	140	14.8
Preparation	606,400	3.4	45	4.8
Storage and transportation	97,900	0.6	5	0.5
Combustion	1,121,800	6.4	42	4.5
Coke and chemicals	5,435,400	31.3	273	28.9
Gasification of coal	2,517,900	14.5	91	9.7
Coal hydrogenation	2,080,100	12.0	93	9.8
Physical and chemical properties	1,005,600	5.8	68	7.2
	17,382,400	100.0	944	100.0

* Bituminous coal trends: National Coal Association 1956, p. 139.

Contributed by:

	Dollars
Federal agencies	4,863,737
State agencies	579,727
Commercial coal	2,452,284
Captive coal	1,206,888
Equipment manufacturers	3,220,810
Other industrial	4,954,954
University and unidentified	104,000

The general character of coal research as it is viewed by the National Coal Association, which is management, is indicated by the information contained in Table 1 (NCA, p. 139).

This and other information provided by the National Coal Association show that the main research emphasis (64.2 percent) is in the field of utilization, that is carbonization, gasification, combustion, and hydrogenation. Carbonization concerns about one-quarter of the cost of the projects upon which the tabulation is based, and nearly 30 percent of the personnel. Furthermore it is the only field in which federal, state, university agencies, and research institutions have all been engaged.

In the field of mining and transportation the research and testing activities represent about 21.5 percent of the total outlay for research. The projects in this field have been largely the concern of research institutions and industry, although the universities are working on problems of continuous mining and roof control and the federal government is making a study of auger mining.

Only two of the nine classes of research listed appear to be related to coal geology, namely the two designated Coal Resources and Physical and Chemical Properties. The last item, however, refers mainly to activities concerned with sampling and analysis, much probably of a routine character. It is possible that the carbonization studies (coke and chemicals) may include certain studies involving the relation of coal petrology to carbonization underway in the Coal Research Section of the College of Mineral Industries, the Pennsylvania State University, under the direction of William Spackman, Jr., in part supported by industry. In general, however, we are chiefly concerned with investigations of geological character that represent an expenditure of nearly $1½ million and the activities of 187 professional individuals representing 8.5 percent of the funds and 198 percent of the man power devoted to all coal research.

Since the National Coal Association specifically differentiates coal resources studies, in its classification of coal research activities, from the several categories of applied research dealing with mining and utilization it becomes pertinent to inquire into the nature of these activities, their character not being immediately apparent.

COAL GEOLOGY AS AN ASPECT OF COAL RESEARCH

The geological investigations which are included under the heading of Coal Resources in Table 1 consist of two fields of geological activity: coal resources investigations and investigations in the field of "coal petrology, geology, and other earth sciences as applied to resources" (NCA, p. 45). This subdivision is a natural one, and is in accordance with the general practice in geological surveys under state or federal jurisdiction. One field has to do with the discovery, mapping, distribution, thickness, and minability of the coal beds, and the quality of the coal contained therein, as determined by the conventional methods of face sampling and chemical analysis. The other branch is concerned with the coal material itself, rather than as a coal bed, that is with its origin, physical constitution and structure.

Coal Resource Studies.—A little more than $1 million was used in 1955 by federal and state governments, universities and research institutions in coal resource studies, including an unspecified amount used in the study of trace elements of various kinds found in coal beds. Probably the greater number of the individuals counted are employees of federal and state geological surveys who are mapping the outcrops and structure of coal beds and making determinations of coal reserves.

The emphasis placed upon this type of geological work is understandable, for there is increasing need for the best possible knowledge concerning the location, quality, and availability of our bituminous coal resources. Coal geology of this kind absorbs much the larger proportion of the funds assigned to the general field of coal geology. Unfortunately it seems to be the general idea that this type of work does not require a great deal of special training or instruction. Accordingly there are commonly assigned to work in this field young men recently from college with little or no special training other than in the field of general geology. It is usually the case that after a little field experience and with good supervision in a short time they may become competent to map easily recognizable sedimentary horizons, coal beds or otherwise, and to work out structural features presenting no unusual difficulties. Not uncommonly such a young geologist is more troubled with problems of field transportation and maintenance than with mapping or description of the coal bed itself. Lacking suitable instruction, too frequently the nature of variations to which the coal bed is subject is little understood and inadequately or entirely unrecorded. Variations in roof and floor and the significance of stratigraphic variations affecting the associated rocks which may mean much in their effect upon ease of recovery of the coal may be entirely overlooked. Particularly, it is often the case that an understanding of the structural or constitutional make-up is lacking, upon which knowledge alone a suitable description of a coal bed can be based, to say nothing of the ability to use the fossil plant components of the coal as a means of solving problems of stratigraphic correlation.

This idea that experience in coal geology is sort of an initiating procedure in geological training is due for a change. The long prevailing idea of the relative unimportance of the mapping of coal resources to the coal industry, which can possibly be largely ascribed to the supposed inexhaustibility and ready availability of supplies of good coal no longer holds true. From the experiences of the coal industry, public utilities, steel and aluminum companies, and others in locating large bodies of workable coal as reserve supplies, it is being realized that such coal must be geographically well located and possess desirable geological and chemical characteristics. With the increasing specificity of requirements for each particular type of utilization and installation the search for suitable bodies of coal is becoming increasingly rigorous. I believe that schools and colleges, particularly those located in or adjacent to the bituminous coal fields, should consider this situation in planning curricula. It seems doubtful whether the conventional courses in economic geology in most cases provide the necessary instruction about coal and coal beds to equip an

individual with training and knowledge necessary for the correct evaluation of a particular coal deposit.

Coal Petrology.—We may now turn to a consideration of the other phase of coal geology which is somewhat more adventurous in character because of its relative novelty and the general lack of understanding of its significance in the field of applied or economic geology.

The science of Coal Petrology is like that type of construction, to which writers have more or less frequently referred, with two teams of architects, one team building from the roof down and the other from the ground upward. The two schools of coal science, that is the architectural teams, to which reference is made are the American school of Coal Microscopists, which follows the system of description and nomenclature marked out by Reinhardt Thiessen, and the European school of Coal Petrologists that recognizes Marie Stopes as its leader. The first, or American, group is building on a foundation of painstaking study of the coalified fossil plant material present in coal. The main elements of construction are the microscopically identifiable constituents anthraxylon, translucent and opaque attritus and the uniquely coalified substance fusain, and the numerous plant organs, secretions, and derivatives sometimes called phyterals, such as bark, wood, spores, cuticles, or resin bodies, identifiable as plant fossils.

The European group of coal petrologists, on the other hand, prefer basic subdivisions of coal material as such, which are readily recognizable with the unaided eye in bituminous coals as the four banded ingredients now called lithotypes or rock types, vitrain, clarain, durain and fusain. It is from this over-riding subdivision of coal material that the coal petrologists have extended downward a science structure that reaches toward but does not quite match with that being built upward by the coal microscopists. Fusain seems to be the one construction beam which both systems have in common, and it does not provide much leverage for the good correlation of the two systems of construction.

One of the reasons for the more or less independent development of these two schools of coal petrology and coal microscopy resides in the prevailing use by the American coal microscopists of thin sections of coal viewed in transmitted light, and the predominant use by European coal petrologists of polished surfaces of coal viewed in reflected light. General substitution by European coal technologists of the polished surface for the thin section method may at least in part be ascribed to the discovery that the use of oil immersion objectives effected resolution of the reflected image to a degree that made unnecessary the preparation of thin sections for most of the practical applications of coal petrology.

Microscopic resolution of the four lithotypes or rock types of coal recognized by the European school into constituent parts was, of course, inevitable. This resolution resulted, however, not so much in the recognition of fossil plant forms, organs, and secretions as in recognition of varieties of coal or macerals. The macerals compose the lithotypes in a manner similar to minerals in inorganic rocks. Thus the emphasis was on the designation of the maceral as a particular variety of coal material rather than as a fossil entity.

To make provision for the various proportions of the macerals composing the different varieties of bituminous coal a fairly complicated system of classification and nomenclature has been devised. In order to simplify the classification and description, particularly in the field of applied petrology there has developed a simplified system attained by combining certain macerals of similar general characteristics into groups. Thus, in the last few years three groups of macerals or group macerals are regarded as representing in general the three varieties of material composing bituminous coal. These are the humic type of maceral represented by vitrinite and constituting that part of coal derived from woody substances; the bituminous type of coal material or exinite consisting of that part of the coal composed of waxy and resinous substances; and finally the macerals of high carbon content represented by fusain and other opaque or nearly opaque material and designated by a variety of names such as micrinite, inertinite, and carbinite. This system of group maceral classification and nomenclature has been put into use in many foreign countries as a means of describing and classifying coal material for practical purposes. It has several advantages in its favor: It is relatively simple, the varieties of coal material are grouped into three categories of more or less distinctive properties; and the composition of a coal in terms of the group macerals can be readily indicated on a ternary chart. There is nothing strictly comparable to such an arrangement in the American system of coal microscopy. There still remains some question, however, whether the simplicity of classification imposed by the group maceral system adequately represents the complete range of possible variability.

The European coal petrologists have been striving to internationalize the language of coal petrology, particularly with respect to the applied aspects of the science and to provide a glossary of coal description of an international character. This activity has been underway since the formation of the International Committee on Coal Petrology at the last Conference on Carboniferous Stratigraphy at Heerlen in 1953, in which committee American representatives have had some part. These efforts will presumably soon bear fruit in the publication of the first edition of the glossary consisting of about 40 terms during the coming winter. This achievement will, however, not resolve all the difficulties in terminology and definition in terminology, definition, and concepts separating the European coal petrology and American coal microscopy in the construction of a unified science of coal petrology.

APPLICATION OF COAL PETROLOGY TO THE COAL INDUSTRY

The lack of complete agreement, accompanied by some misunderstanding and confusion, existing between the American and European groups of coal microscopists and petrologists should not distract our attention from and discourage recognition of the practical importance of the state of physical heterogeneity existing in coal, whatever the components or constituents are called. The fact of this heterogeneity exists, whether it is expressed in terms of plant parts of phyterals, or in terms of coal components or macerals. For about forty years the literature of coal geology has contained many references to the physical heterogeneity of coal, until now the idea is generally accepted.

The part this knowledge may play in the operation of the American bituminous coal industry is, at least, indicated by the application of coal microscopy to the selection and blending of coal in the manufacture of metallurgical coke, particularly in European countries. Similar applications are now under investigation in several coal petrology and coal geology laboratories in this country and Canada.

The possibility of still further application is to my mind strongly suggested by the situation in which the bituminous coal industry finds itself in the field of coal preparation, the tendencies in which have already been indicated. The increase in the production of fine coal together with the mechanization of mining operations has enhanced the importance of cleaning processes in order to produce coal of low ash content. Eventually, I believe, this trend will reach a limit of practical achievement in the improvement of such fine coal in terms of ash content. However, in the fineness of the coal and in the heterogeneity of its petrographic composition there exists further possibilities of modification and in the preparation of coals of specific type.

Within the past two or three years the possibility of separating coals of high and medium volatile rank into three predominant types of coal material, vitrinite, exinite, and micrinite, when finely pulverized, seems to have been successfully demonstrated in several laboratories in Europe, particularly at Aachen and Essen in Germany, and in Geleen in the Netherlands. Concentrations demonstrated by microscopic examination to be above 90 percent have been achieved for each type of material in quantities adequate to provide material for chemical and physical tests. Although it was found that differences among the maceral groups tend to fade out in the higher rank coals, they are very real in the medium and particularly in the high volatile coals such as those that form the greater part of the production of bituminous coal from American mines. In view of what appears to be a steady trend toward an increase in the production of fine sizes of coal, the lesson of coal petrology points to the eventual utilization of this science in the production of special types of coal by existing or more refined methods of preparation, but prepared under petrographic laboratory control.

To believe that the possibility of this sort of change in the nature of the preparation of coal resides by nature in the coal industry would reveal a lack of understanding of the manner in which changes take place in this industry. In most cases they are in response to changes in the market. Hence in this case likewise the market probably must be modified into forms that emphasize the importance in utilization practices of variations in coal type owing to the specific concentrations or reductions in the petrographic components. This eventuality, if realized, must wait demonstration supplied initially by academic and other fundamentally scientific laboratories sufficiently interested to explore the possibilities of the field not only along lines being followed by our colleagues overseas but with a true spirit of exploration and research.

Illinois State Geological Survey,
Urbana, Illinois,
Dec. 9, 1957

Economic Geology
Vol 53, 1958, pp. 521–545

THE CHEMICAL ENVIRONMENT OF PITCHBLENDE

LEO J. MILLER

CONTENTS

	PAGE
Abstract	521
Introduction	521
A review of the literature	522
Acknowledgments	523
Methods of uranium analyses	523
The Jones reductor method	523
Colorimetric method	524
X-ray analyses	526
Stability measurements	526
Electrometric titrations	526
Solubility measurements	527
High temperature and high pressure apparatus	527
The stability of several natural occurring uranium ions and the conditions under which they react to form pitchblende	529
The uranyl and uranyl sulfate complex ions	529
The uranyl hydroxide complex ion	532
The uranyl carbonate complex ion	536
The uranyl fluoride complex ion	538
The uranous ion	540
The effect of foreign cations on uranium complexes	542
The role of pressure in pitchblende synthesis	542
Summary	543
References	544

ABSTRACT

Several uranium complex ions have been found to be stable over a wide range of pH, temperature, and pressure. At 25° C and in neutral solutions uranyl complexes of carbonate, fluoride, and hydroxide remain in solution at concentration values between 10^{-5} M and 10^{-3} M. At elevated temperatures (215° C) the solubility of these ions at pH 7 is still above 10^{-5} M.

At 25° C the above mentioned ions will react with a reducing agent (H_2S) at pH 7 to form pitchblende of small crystallite size. A similar reaction proceeds at elevated temperatures (215° C) and pH 7, but the pitchblende precipitates with larger crystallite dimensions.

The uranous complex ions are relatively unstable. Solutions of uranous hydroxide precipitate a small amount of pitchblende at 25° C. At elevated temperatures (215° C) all of the uranium in solution converts to well crystallized pitchblende.

INTRODUCTION

THIS paper describes an experimental study on the synthesis of pitchblende undertaken as a research project for the Division of Raw Materials of the

Atomic Energy Commission. The experimental work was in progress between October 1953 and May 1955. The purpose of the work has been to develop knowledge applicable to the emplacement of pitchblende in ore deposits. Two experimental studies were made: (1) the stability in solution of those uranium ions that precipitate as pitchblende, and (2) the conditions of precipitation. Only inorganic systems were investigated.

Throughout the work conditions of stability and precipitation were chosen that might conceivably have occurred in nature. At the same time the physico-chemical systems were not made so complicated that fundamental facts would be obscured. It is realized that this work has not duplicated many conditions in natural ore solutions. To bring about complete simulation many foreign cations not considered in this work should have been introduced. Before this can be done studies should be completed on the stability and mineral precipitation of metal ions such as lead (galena), zinc (sphalerite), iron (pyrite), and copper (chalcopyrite), in the presence of common anions used in this experimental investigation (S^{-2}, S^{+4}, SO_4^{-2}, Cl^{-1}, F^{-1}, CO_3^{-2}, HCO_3^{-1}).

A Review of the Literature.—Between 1824 and 1930 several chemists successfully produced pitchblende (UO_2) in the laboratory. From 1927 until 1940 little experimentation was reported on the chemistry of uranium oxides. During and after the war much literature was published concerning UO_2. Little of this work has a direct bearing on the synthesis of pitchblende from solution, but deals primarily with the dry fusion of uranium salts with a variety of chemical compounds that produce UO_2, UO_3, and U_3O_8.

Arfredson (2) obtained UO_2 by reduction of KUO_2Cl_3 with dry hydrogen. Ebelman (6) claimed to have precipitated pure cubic crystals of UO_2 from $NaUO_4$. Wöhler (32) treated a solution of $(NH_4)_2UO_4$ with HCl and an excess of NH_4Cl, and after evaporation, fusing, and leaching he obtained UO_2. Kessler (19) dissolved UO_2 with HNO_3 and reprecipitated it with H_2S at a temperature of 30° C. Hillebrand (13) confirmed Wöhler's experiment of 1942. Oechsner de Connick (26) produced UO_2 from $UO_3.H_2O$ by reduction with hydrogen at a low red heat. Ipatieff and Muromtsev (15) reduced uranyl nitrate solutions to UO_2 with hydrogen gas. Katz and Rabinowitch (16) summarized the precipitation of UO_2 by stating: "Uranyl salts can give UO_2 either by straight thermal decomposition, e.g.,

$$UO_2Br_2 \xrightarrow{\text{heat}} UO_2 + Br_2$$

or by reduction, e.g.,

$$UO_2Cl_2 + H_2 \rightarrow UO_2 + 2HCl."$$

Gruner (9) demonstrated that pitchblende would precipitate from acid (pH 2) uranyl solutions from 50° C to 215° C by using either H_2S or organic reagents. Long (21) published an annotated bibliography on the solid state reactions of the uranium oxides.

Although early work had been done on the composition of uranium ions most of the recent work has been carried on by various Atomic Energy Commission research projects. Pisani (25) did the early work on the carbonate complexes and Wilder (31) has done recent work on the composition of the uranyl carbonate complex. Pascal (27) investigated the stability of uranium hydrophosphate and uranium pyrophosphate. Kunin (20) determined the stability of the uranyl ion as a function of pH. Harned (11) worked on mixtures of uranium IV and uranium VI.

Most of the stability investigations to date are of little use to the geologist. This results because concentrations of uranium ions above neutralization amounts have not been obtained and the stability of the uranium ions at elevated temperatures have not been investigated.

Since the writing of this report Garrels (8) has published additional data on the thermodynamic relations of uranium oxides and Gruner (9) has published the results of his recent geochemical experiments.

Acknowledgments.—The writer is greatly indebted to Professor Paul F. Kerr, Department of Geology, Columbia University, for his guidance and constructive criticism on the overall program. Professor T. Ivan Taylor, Department of Chemistry, Columbia University, supervised the chemical program and gave much assistance in chemical procedure and construction of experimental apparatus. William Croft of Columbia University made the determinations of crystallite size. The Raw Materials Branch of the Atomic Energy Commission provided the funds for the research, and published a preliminary paper as RME—3110 (Pt. 1) 1955.

METHODS OF URANIUM ANALYSES

Two analytical procedures were used for the determination of uranium in solution, each depending on the concentration of the sample. The Jones reductor with a potassium permanganate titration was used for the analyses of solutions with a uranium concentration of 10^{-3} M or greater. Solutions with uranium concentrations between 10^{-4} M and 10^{-6} M were analyzed by colorimetric methods. All precipitates were analyzed by x-ray diffraction methods.

The Jones Reductor Method.—This method of analysis depends upon the quantitative oxidation-reduction of uranium. In the Jones reductor, uranium is quantitatively reduced to uranium (IV) and uranium (III), then aerated completely to uranium (IV), and finally titrated to uranium (VI) by means of a suitable oxidant.

The Jones reductor used in these experiments was a 6-inch column of amalgamated zinc in a cylindrical reduction tube. Solutions of uranium, in 4N sulfuric acid, were allowed to pass through the zinc column at a rate of 15 ml per minute. The column was then washed thoroughly with 4N sulfuric acid and finally by water. The resulting mixture of uranium (IV) and (III) was aerated by rapid agitation with a magnetic stirrer to insure oxidation of red uranium (III) to green uranium (IV). Quadravalent uranium is stable in the presence of air for a few hours but over a period of days is completely oxidized to uranium (IV). The solution of uranium

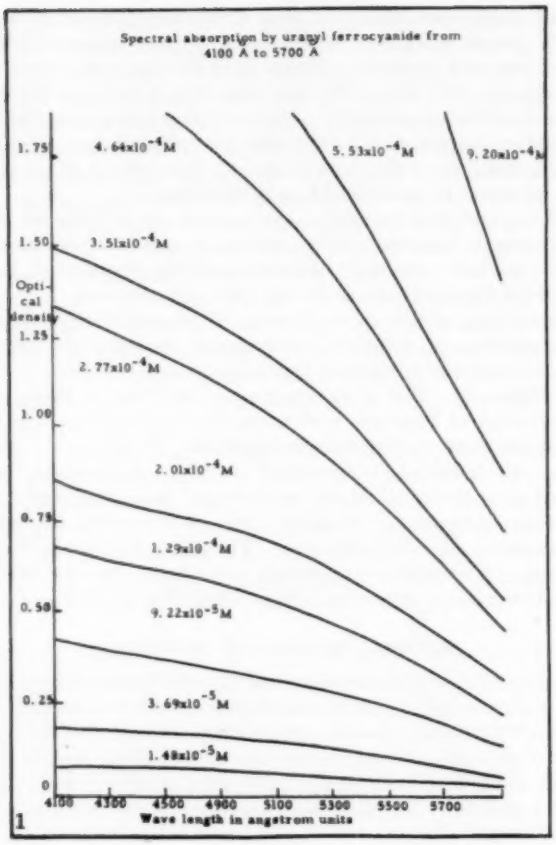


FIG. 1. Spectral absorption by uranyl ferrocyanide from 4,100 Å to 5,700 Å.

(IV) with a concentration above 10^{-3} M was then titrated with a 0.1 N potassium permanganate solution that had previously been standardized with arsenious oxide. The precision of the determinations is 0.1 percent. For a detailed discussion of this method see Rodden (1950, pp. 54–57, 65, and 68).

Colorimetric Method.—The bulk of the uranium analyses were determined with the Cary Spectrophotometer. The analytical results were obtained from an equation based on Beer's Law:

$$\log \frac{I_0}{I_0} = - \xi \, cl$$

where I_0 is the original intensity of the incident light, I is the intensity after passing through a medium of thickness 1, ξ is the molar absorption coefficient, and c is the concentration of the absorbing medium. The law states that the ratio of the transmitted light to the original light is proportional to the light path and concentration. The Cary Spectrophotometer auto-

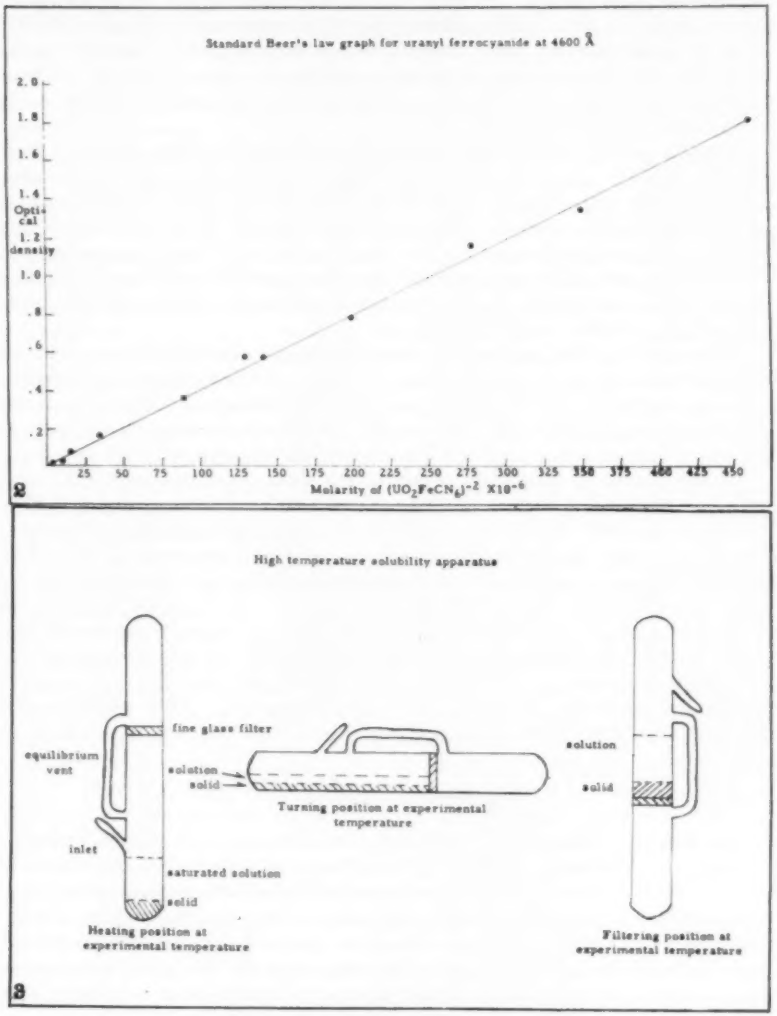


FIG. 2. Standard Beer's law graph for uranyl ferrocyanide at 4,600 Å.
FIG. 3. High temperature solubility apparatus.

matically records the absorption spectra in both the ultraviolet and visible regions. The Model 11 spectrophotometer records optical density on a linear scale from 0–2.5 and 1.0–3.5.

There are several complexing compounds that give colored uranium complex ions. The complexing agent used in these experiments was potassium ferrocyanide. Uranyl ions in acid sulfate solutions react with ferrocyanide to give reddish-brown uranyl ferrocyanide $(UO_2Fe(CN)_6)^{-2}$. This ion absorbs light from 3,000 Å to 6,000 Å (Fig. 1). Several curves demonstrated that the optical density is directly proportional to uranium concentration (Fig. 2). The maximum deviation of a concentration value from a straight line is 2.5 percent.

The procedure used in the preparation of solutions was modified from Harvey (1944). To a uranium solution of 0.1 ml to 5 ml (concentration less than 10^{-3} M) was added 5 ml of 0.237 $MK_4Fe(CN)_6.3H_2O$ with a small amount of $Na_2SO_3.7H_2O$. This was then diluted to 25 ml with 0.1 N H_2SO_4. The solution stood for one hour in the dark before a reading was taken. The reddish-brown solution was then poured into 2 cm cylindrical quartz cells and placed in the spectrophotometer. Measurements were taken both at 4,600 Å and 6,000 Å.

The only interfering elements found in these experiments were fluorine and carbonate when in the presence of sulfide. When potassium ferrocyanide was added to sulfide solutions with $UO_2(CO_3)_3^{-4}$ or $UO_2F_6^{-4}$ a white colloidal precipitate formed. Hence all solutions containing these elements were first evaporated in sulfuric acid before complexing with ferrocyanide.

X-ray Analyses.—The solid precipitates were examined with a Norelco diffractometer and a Debye-Scherrer camera with a 57 mm diameter. The diffractometer was used for the precise measurement of lattice constants which for some pitchblendes agreed to ± 0.003 angstrom units. The diffractometer was also used for the measurement of the crystallite size of some pitchblendes. For a detailed discussion on line broadening and crystallite size of the pitchblende synthesized in these experiments the reader is referred to the work of William J. Croft at Columbia University (5). The Debye-Scherrer powder camera was used for the identification of pitchblende and the other synthetic uranium compounds. This method, plus the analytical control of solutions, has been utilized for the recognition of pitchblende.

STABILITY MEASUREMENTS

Electrometric Titrations.—Electrometric titrations were conducted with a Leeds and Northrup universal pH indicator assembly No. 7663-Al. It has an amplifier which draws a very low current from the measuring electrodes (about 2×10^{-12} ampere at balance). This causes an error of only 0.002 volts per 1,000 megohms. The glass electrode, the saturated calomel electrode, and the platinum electrode were used for the various measurements. The pH value was read to the nearest hundredth of a unit but was probably accurate only to the nearest tenth of a unit.

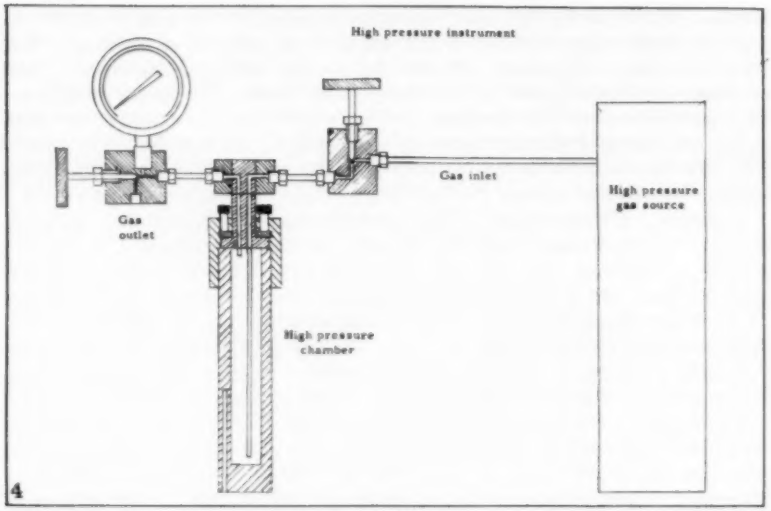
The meter was used for the titration of uranyl solutions with different

anions. E.m.f. and pH measurements were taken at various intervals depending on the concentration of the solutions and speeds of reaction. The solutions were in constant agitation before and after all readings. Most titrations were carried out in a closed system with a nitrogen atmosphere. This was done primarily because of the complexing of uranium ions with carbonate ion and the oxidation of uranium IV to uranium VI. Some difficulty was encountered with fluorine anions due to their reaction with silica. This was overcome by rapid titration in the low pH range.

Solubility Measurements.—The concentration of a particular uranium ion at various pH values and the foreign ion concentration at 25° was not difficult to measure. It was only necessary to analyze a portion of a uranium solution which had been in equilibrium with its precipitate for several days. For measurements at higher temperatures a glass bomb was designed with the help of Dr. T. Ivan Taylor, Department of Chemistry, Columbia University, which made it possible to isolate the solution from its precipitate at elevated temperatures. This solution could then be cooled and analyzed. The bomb is illustrated in Figure 3. The saturated solution within the bomb was heated to the desired temperature and was kept at that temperature for 24 hours to allow the system to come into equilibrium. The bomb was then slowly turned to permit the solution to filter through a fine glass frit, and at the same time care was taken not to allow the solution to pass through the open equilibrium vent. When the filtration was complete the bomb was cooled and the lower portion containing the solution was analyzed. The amount of uranium in this solution indicated the solubility of uranium under those conditions of temperature, pressure, pH, etc. controlled in the experiment. This bomb was also used for direct precipitation and solubility measurements.

High temperature and high pressure apparatus.—All of the high pressure experiments were conducted in an American Instrument Company microreaction vessel (Fig. 4). Pressures of 10,000 lbs/in.^{2} can be obtained at 400° C. Most of the experiments at 25° C were carried out at pressures below 2,200 lbs/in.^{2}. This is the tank pressure of most gas cylinders. Higher pressures were obtained by heating. To obtain pressures up to 10,000 lbs/in.^{2} it is necessary to insert a booster pump between the gas cylinder and the bomb. The high pressure vessel is not able to take measurements of pH, e.m.f. and solubility at these high temperatures and pressures. Morey (1955) of the Geophysical Laboratory has used a modified Bridgeman type reaction vessel to solve the solubility problem. Metal-metal electrodes and oxidation-reduction electrodes are available which can withstand high temperatures and pressures but bombs with high pressure seals for the electrodes are not believed to exist.

To make synthetic pitchblende under high pressures, uranium solutions were first placed in a pyrex liner within the reaction vessel. The vessel was then sealed and a reactive gas such as hydrogen sulfide, or an inert gas such as nitrogen, was bubbled through the solution at 25° C and flushed out through the outlet valve. After closing the outlet valve the pressure was increased by the nitrogen gas. The system was then heated and the tem-



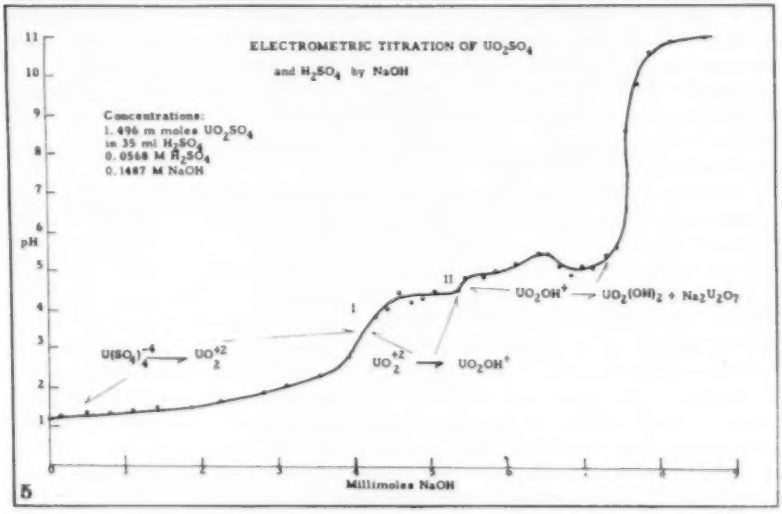


FIG. 4. High pressure instrument.
FIG. 5. Electrometric titration of UO_2SO_4 and H_2SO_4 by NaOH.

perature was measured by chromel-alumel thermocouples attached to a Leeds and Northrup double range potentiometer indicator No. 8657-C. The temperature was accurate to ± 5° C. The pressure was measured by an Acragage pressure gauge and is probably accurate to ± 100 lbs/in.^{2}.

THE STABILITY OF SEVERAL NATURAL OCCURRING URANIUM IONS AND THE CONDITIONS UNDER WHICH THEY REACT TO FORM PITCHBLENDE

The term stability, generally employed in problems concerning mineral synthesis from solution, is defined as the ability of a particular ion to remain in solution. In this special study of uranium ions stability is considered as a function of temperature, pressure, uranium concentration, and certain anion concentrations including pH, and time.

From the standpoint of natural occurrence there are two important valence states of uranium, the tetravalent and hexavalent. Trivalent and pentavalent states exist but are not considered important in the formation of stable ions in nature. The trivalent state is readily oxidized by small amounts of oxidants and is only formed under rigid reducing conditions. Pentavalent uranium is a transitory valence state with respect to its disproportionation into tetravalent and hexavalent uranium. Furman and Watters (p. 580) state that "recent work strongly indicates that a small amount of uranium (V) remains in equilibrium with the other two states." In view of these considerations the complex ions investigated in this work have been separated into two groups, the tetravalent and hexavalent.

Only those uranium ions that are believed likely to occur in natural solutions were studied. Complex ions such as the uranyl cyanide and uranyl nitrate, although known in the laboratory, are not considered probable uranium-transporting agents in nature. This seems reasonable since cyanide and nitrate minerals are lacking in pitchblende deposits. Uranyl carbonate and uranyl fluoride ions, however, have been investigated since carbonate and fluoride minerals are commonly associated with pitchblende deposits (3). Table I lists the uranium ions studied. $UO_2(CN)_4^{-2}$ and $UO_2(NO_3)_4^{-2}$, although known uranium ions, have not been included. The stability of the uranyl hydrophosphate ($UO_2H_2PO_4^{+1}$) and uranyl pyrophosphate ($UO_3P_2O_7^{-2}$) are being measured. Organic uranium complex ions have not been studied.

THE URANYL AND URANYL SULFATE COMPLEX IONS

Salts of uranyl sulfate dissolve in water forming the light yellow UO_2^{+2}, $UO_2(SO_4)_2^{-2}$, and $UO_2(SO_4)_3^{-4}$ ions (29). The pH of the solution is dependent upon the uranium concentration and may vary from pH 4.2 to pH 1.5 (23). The predominant ion is UO_2^{+2} at moderate sulfate concentration $U^{+6}/SO_4^{-2} = 1/1$.

The compositions of these ions were inferred by potentiometric titration of uranyl sulfate solutions with sodium hydroxide (Fig. 5). In the absence

TABLE I

URANIUM IONS STUDIED IN THIS REPORT

UO_2OH^+	$UO(OH)^{+1}$
$UO_2(CO_3)_3^{-4}$	$UO(CO_3)_2^{-2}$
$UO_2F_6^{-4}$	UOF_3^{-1}
$UO_2(SO_4)_2^{-2}$	USO_4^{+2}
$UO_2Cl_4^{-2}$	UCl_4^{-2}
UO_2^{+2}	

of sulfate it should take 3 millimoles of NaOH to convert 1.5 millimoles of a UO_2^{+2} solution to $UO_2(OH)_2$. From the data of Figure 5 it takes 3.7 millimoles to accomplish this conversion and therefore an ion other than UO_2^{+2} is present. From the stoichiometry it is postulated that 1.2 millimoles of UO_2^{+2} are associated with 0.3 millimoles of $UO_2(SO_4)_3^{-4}$ at pH 2. At pH 3.5 conversion to $Na_2UO_2(SO_4)_3^{-2}$ and $UO_2(OH)^{+1}$ begins and is completed by pH 4.5. Above pH 4.5, $Na_2U_2O_7$ and $UO_2(OH)_2$ precipitate. As a function of pH the uranyl and uranyl sulfate ions are stable below pH 3.5 at 25° C.

The stability of the uranyl and uranyl sulfate ions is affected by the presence of hydroxide, carbonate, fluoride, phosphate, pyrophosphate, and sulfide anions. The complexes which these anions form with uranium will be discussed under subsequent titles.

Pure uranyl and uranyl sulfate complex ions are stable from 25° C to 300° C below pH 3.5. In the presence of reducing agents such H_2S, SO_2 or H_2 these complexes are reduced to UO^{+2}, $U(SO_4)_3^{-2}$ or $U(SO_4)_4^{-4}$, depending on the sulfate concentration. At temperatures ranging from 50° C to 300° C the tetravalent uranous ions precipitate as pitchblende (Gruner, 1952).

When a pure uranyl sulfate solution is saturated with H_2S at 25° C and pH 2, partial reduction to UO_2^{+2} and $U(SO_4)_3^{-4}$ takes place. In this reaction each sulfide ion contributes 2 to 8 electrons to the hexavalent uranium atoms, and is converted to sulfur and sulfate. When this solution is heated in a closed system the sulfur is converted to SO_4^{-2} which reduces more uranium. The uranous ion reacts with water to precipitate pitchblende.

$$UO^{+2} + H_2O \rightarrow UO_2 + 2H^+$$

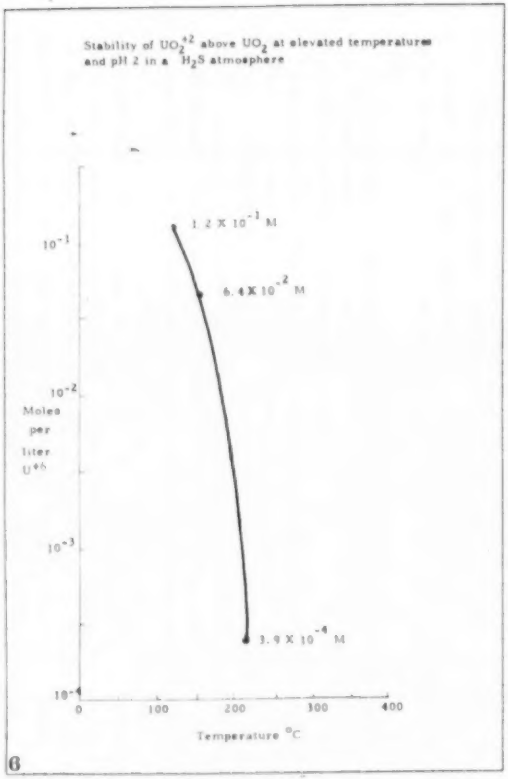
The authenticity of the above reaction is based on four lines of evidence: (1) the solutions turn green after introduction of H_2S because of the formation of U^{+4}, (2) the pH drops due to the ionization of H_2S and conversion of sulfide, (3) the e.m.f. changes from + 0.2585 to − 0.0645 volts because of the change in equilibrium of the couples:

$$UO_2^{+2} + 4H^+ + 2e = U^{+4} + 2H_2O \text{ (Latimer, 1953)}$$
$$S^{-2} + 4H_2O = SO_4^{-2} + 8H^+ + 8e$$

and (4) X-ray data of the black precipitate are identical to pitchblende.

The concentration of uranium in equilibrium with pitchblende depends on temperature. Figure 6 is a curve of solubility of pitchblende in equilibrium with UO_2^{+2} plotted against temperature. At 215° C the solubility of pitchblende is 3.9×10^{-4} M.

The pitchblende precipitated under these conditions is a black, hemispherical, betryoidal material in a brown groundmass (25). According to Croft (5) the spherules consist of parallel fibers elongated along axes polar to 111 planes. The crystallite size varies with the temperature of precipitation from 100 angstrom units at 135° C to 500 angstrom units at 215° C.



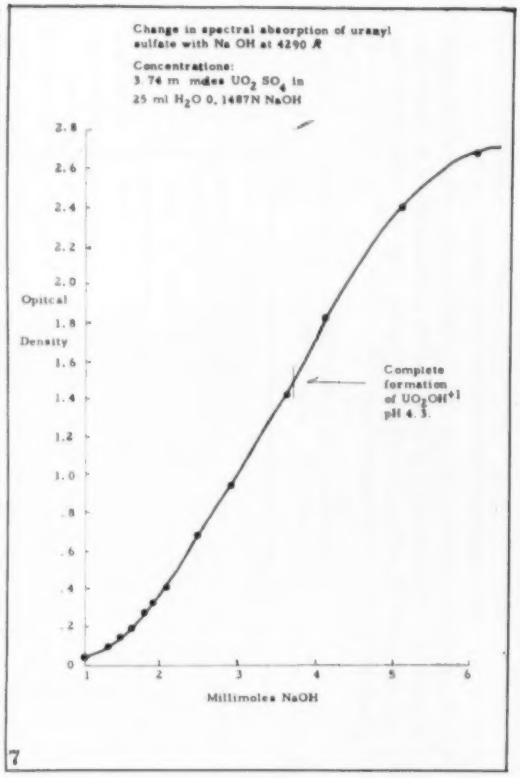


FIG. 6. Stability of UO_2^{+2} above UO_2 at elevated temperatures in a H_2S atmosphere at pH 2.0.
FIG. 7. Change in spectral absorption of uranyl sulfate with NaOH at 4290 Å.

The microscopic texture of the synthetic pitchblende is similar to the pitchblende from the Front Range deposits and Great Bear Lake in that gray bands are circularly distributed throughout the hemispheres.

THE URANYL HYDROXIDE COMPLEX ION

The uranyl hydroxide complex ion is deep yellow in contrast to the light yellow uranyl ion. The formula is $UO_2(OH)^{+1}$, as determined by potentiometric titrations of UO_2SO_4 solutions with NaOH (Fig. 5). Part II of the curve indicates the following equilibrium:

$$\underset{\text{uranyl ion}}{UO_2^{+2}} + OH^- \rightleftarrows \underset{\text{uranyl hydroxide ion}}{UO_2OH^+}$$

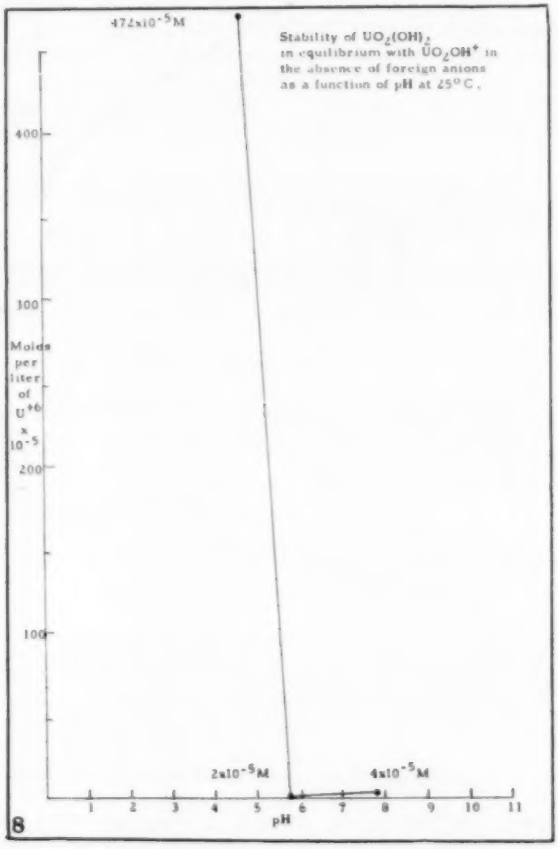


FIG. 8. Stability of $UO_2(OH)_2$ in equilibrium with UO_2OH^+ in the absence of foreign anions as a function of pH at 25° C.

At the first break in the curve 4 m moles of NaOH have neutralized 2 m moles of H_2SO_4. At the second break in the curve 1.5 m moles of OH^- have been added to 1.5 m moles of UO_2^{++}. Approximately one m mole of UO_2^{++} combines with one m mole of OH^- giving UO_2OH^+.

Confirmation of this composition was obtained with the spectrophotometer (Fig. 7). The UO_2OH^{+1} ion has two absorption peaks at 3350° A and 4290° A. As alkali is added to UO_2^{+2} in solution the $UO_2(OH)^+$ increases in concentration and absorption increases. A curve of hydroxide concentration against optical density has a stoichiometric point at 3.7 m moles of OH^- concentration. At this point the formation of $UO_2(OH)^{+1}$ is completed. Beyond this point $UO_2(OH)_2$ precipitates.

As a function of pH at 25° C, the uranyl hydroxide ion is stable from 3 to 4.5 (Fig. 5). The uranyl ion is stable below pH 3. Above pH 4.5, $UO_2(OH)_2.xH_2O$ precipitates as a hydrous yellow crystalline compound. The composition of this compound was inferred from the stoichiometry of Figure 5. Precipitation takes place until 3.2 m moles of OH^- have been added. For every m mole of U^{+6} there are approximately two OH^- m moles. The stoichiometry error is 7 percent. This is attributed to the formation of $Na_2U_2O_7$. The stoichiometric error varies with sulfate and uranium concentrations.

The degree of instability of the UO_2OH^+ ion above pH 4.5 at 25° C is illustrated by Figure 8 which is a curve of uranium concentration against pH. At pH 4.7, 1.12 grams of uranium are present in one liter of solution. This concentration drops rapidly to .004 grams of uranium per liter of pH 5.8. The concentration rises to .01 gram per liter at pH 7.7. The uranyl hydroxide ion is therefore unstable with excess hydroxide ion. Its behavior in the presence of carbonate, phosphate, fluoride and sulfide will be discussed later.

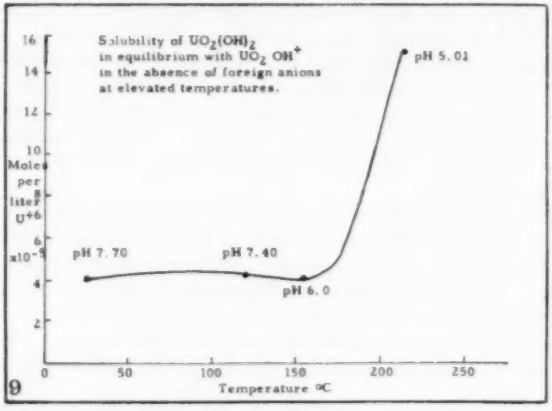
At temperatures greater than 25° C, the UO_2OH^+ ion is less soluble over the entire pH range than at 25° C. Figure 9 is a curve of concentration of uranium against temperature at pH 7.

The uranyl hydroxide ion will precipitate as pitchblende in the presence of H_2S, SO_2 and H_2 at temperatures greater than 50° C in experiments lasting 5 minutes to 3 months. Hexavalent uranium is reduced to tetravalent uranium and from this state reacts with water to form pitchblende.

Hydrogen sulfide reacts with the uranyl hydroxide ion at pH 4.5 and a temperature of 25° C to form a brown precipitate, which is probably uranyl sulfide. The pH is lowered depending on the quantity of sulfide ions. The concentration of uranium is 5×10^{-5} M. Uranyl sulfide is unstable at 25° C and converts to pitchblende. The pH drops during the reaction due to the oxidation of the sulfide ion. The magnitude of the total pH drop depends on the H_2S concentration and is usually two pH units. The electromotive force of the system increases from -0.200 volts to $+0.330$ volts depending on the amount of reduction taking place. This rise in e.m.f. is due to the increase of the U^{+4}/U^{+6} ratio. The crystallite size of the pitchblende precipitated at 25° C is very small as shown by diffused Debye-Scherrer lines and by very low diffraction peaks. Pitchblende becomes very well crystallized by heating solid pitchblende in its solution.

The concentration of uranium in solution above the pitchblende is illustrated at two temperatures in Figure 10 which is a curve of uranium concentration against temperature at pH 2.8 in the presence of H_2S. The concentration is low, being less than 5×10^{-6} gms/l at the higher temperatures. It would probably be even less at lower temperatures if enough time were allowed.

The reaction of the uranyl hydroxide ion with hydrogen gas eliminates the solid state reaction. Reduction with hydrogen gas decreases the pH of a uranyl hydroxide solution from 4.5 to 2.8 and forms the more stable uranyl ion at elevated temperatures (200° C). The UO_2^{+2} is converted by reduction to UO^{+2} which reacts with water to form pitchblende.



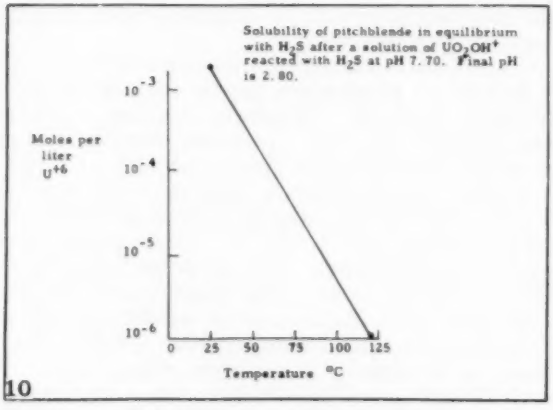
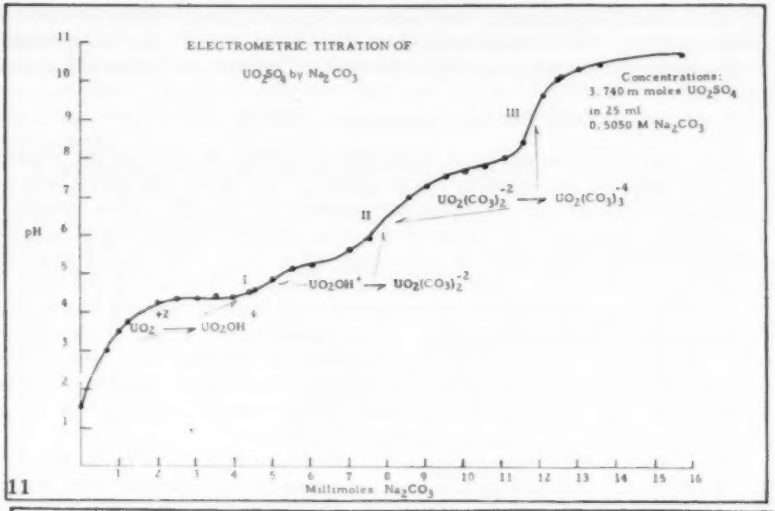


FIG. 9. Solubility of $UO_2(OH)_2$ in equilibrium with UO_2OH^+ in the absence of foreign anions at elevated temperatures.

FIG. 10. Solubility of pitchblende in equilibrium with H_2S after a solution of UO_2OH^+ reacted with H_2S at pH 7.7. Final pH is 2.8.



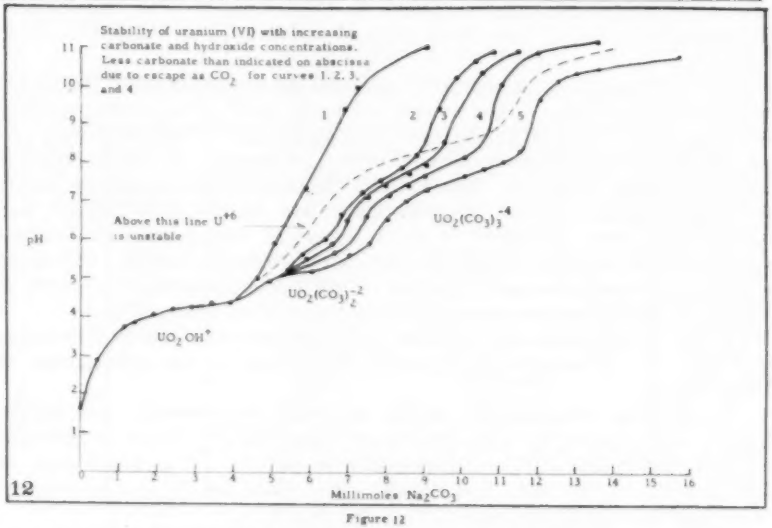


Figure 12

FIG. 11. Electrometric titration of UO_2SO_4 by Na_2CO_3.
FIG. 12. Stability of uranium IV with increasing carbonate and hydroxide concentrations.

All reactions by which the uranyl hydroxide ion is converted to pitchblende take place within a few minutes to several days, depending on the temperature and the concentration of the reducing agent.

The pitchblende precipitated from the uranyl hydroxide-sulfide system

is a black amorphous mass in association with a few transparent orthohombic sulfur crystals. At temperatures from 100° C to 215° C the pitchblende, in its solution, becomes platy while the sulfur converts to yellow spheres.

THE URANYL CARBONATE COMPLEX ION

The uranyl carbonate ion is light yellow similar in color to the uranyl ion. Its formula is variable, being either $UO_2(CO_3)_2^{-2}$ or $UO_2(CO_3)_3^{-4}$, depending on the amount of carbonate present and the pH. The composition of these ions has been inferred by potentiometric titrations of uranyl sulfate solutions with sodium carbonate (Fig. 11). The stoichiometric proportions at the first break in the curve indicate that all of the uranyl ion has been transformed to approximately 84 percent uranyl hydroxide and 16 percent sodium diuranate. The second break occurs at the point where two millimoles of carbonate per millimole of uranium have been added to form $UO_2(CO_3)_2^{-2}$. The third break in the curve is at three millimoles of carbonate per millimole of uranium. Here the $UO_2(CO_3)_3^{-4}$ is completely formed except for small equilibrium amounts.

As a function of pH the $UO_2(CO_3)_2^{-2}$ ion is stable at 25° C from pH 4.5 to 6.5 (Fig. 11). Below pH 4.5, uranyl hydroxide is the stable form while above pH 6.5, $UO_2(CO_3)_2^{-2}$ converts to $UO_2(CO_3)_3^{-4}$. The $UO_2(CO_3)_3^{-4}$ ion is stable to pH 11.5 at which point it precipitates as $UO_2(OH)_2.xH_2O$ (Fig. 11).

The carbonate ion concentration controls the development of the uranyl carbonate ion in place of the uranyl hydroxide ion. If the uranyl solution is below pH 4.5 most of the carbonate ion will escape as carbon dioxide and no carbonate complex will form (Curve 1, Fig. 12). If the solution is rapidly brought to pH 4.5 with sodium carbonate, then enough carbonate is in solution to convert the $UO_2(OH)^+$ ion to the $UO_2(CO_3)_2^{-2}$ and $UO_2(CO_3)_3^{-4}$ ions. Curves 2, 3, and 4, Figure 12, demonstrate the increasing stability of uranium in solution with increased carbonate ion. All of the available carbonate becomes complex at pH 4.5 as illustrated by Curve 5, Figure 12, and therefore no precipitation takes place until pH 11.5.

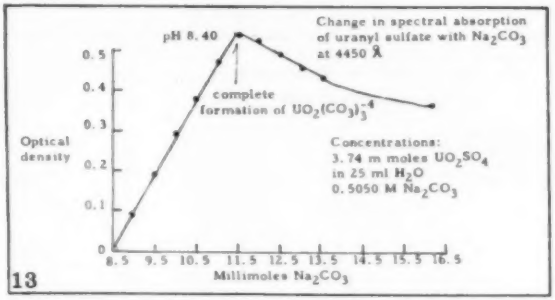
A plot of optical density against carbonate concentration is illustrated in Figure 13. The curve gives an excellent check on the composition of $UO_2(CO_3)_4^{-3}$.

At elevated temperatures uranyl carbonate ions become less stable. Figure 14 is a curve of concentration of $UO_2(CO_3)_3^{-4}$ ions in equilibrium with its precipitate against temperature at pH 9. Its concentration at 215° C is 0.5×10^{-5} M. This is sufficient to place the ion in the category of substantial stability between 25° C and 215° C.

The uranyl carbonate complex ion is stable in the presence of chloride, sulfate, and fluoride. It is less stable with phosphate ion and unstable with the sulfide ion. The concentration of a $UO_2(CO_3)_3^{-4}$ solution saturated with hydrogen sulfide at pH 8 and a temperature of 25° C is less than 10^{-6} M. Copper, lead, and zinc do not cause the precipitation of uranium. Barium causes it to precipitate as the double salt, $Ba_4UO_2(CO_3)_3$ (Hedvall, 1925) (12).

The uranyl carbonate complex ion will precipitate as pitchblende in the presence of H_2S, SO_2 and H_2 at temperatures above 50° C and at all pH values. The sulfide and sulfite ions and hydrogen gas release electrons to the complex. This reduces the uranium from U^{+6} to U^{+4}. The new uranium complex ion (UO^{+2}) reacts with the available water to form pitchblende.

A uranyl carbonate solution at pH 8 saturated with H_2S at a temperature of 25° C precipitates in part as UO_2S which is in equilibrium with a brown uranium sulfide complex ion. Upon standing at 25° C the uranium in solution and the solid UO_2S convert to pitchblende. The concentration of uranium in equilibrium with the pitchblende is less than 10^{-6} M. A bright



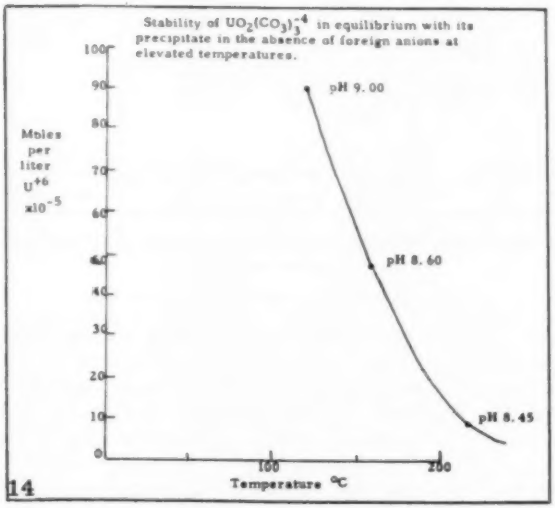


FIG. 13. Change in spectral absorption of uranyl sulfate with Na_2CO_3 at 4450 Å.
FIG. 14. Stability of $UO_2(CO_3)_3^{-4}$ in equilibrium with its precipitate in the absence of foreign anions at elevated temperatures.

yellow ion, which is not believed to contain uranium and may be a polysulfide, forms above the pitchblende. The ion changes to a white colloidal suspension when the solution is made acid. At elevated temperatures the yellow ion changes to blue.

Under the microscope the pitchblende occurs as black shiny sheets. Small orthorhombic, acute pyramidal, crystals of sulfur are present. When the pitchblende in equilibrium with a sulfide-carbonate system is heated above 100° C the pitchblende plates convert to particles resembling small ammonites and the white sulfur crystals change to yellow balls.

Pitchblende precipitated at 25° C has a very small crystallite size. At temperatures above 100° C pitchblende precipitates with large crystallite dimensions.

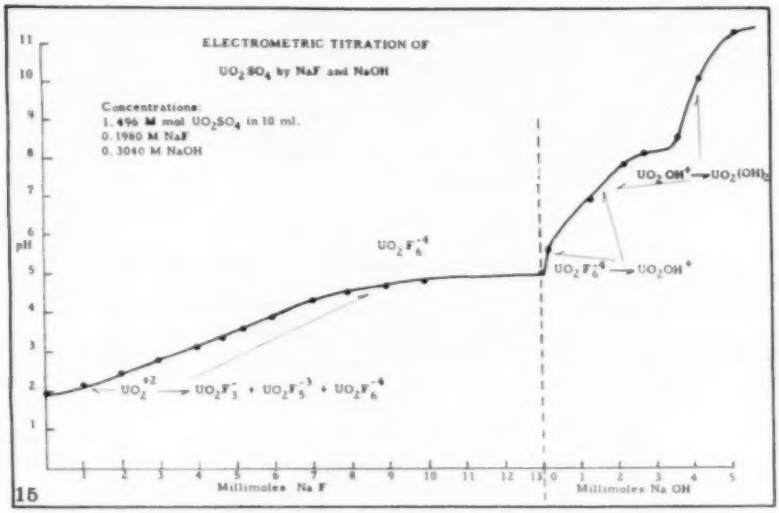


FIG. 15. Electrometric titration of UO_2SO_4 by NaF and NaOH.

THE URANYL FLUORIDE COMPLEX ION

The uranyl fluoride ion is light yellow with a variable composition of $UO_2F_5^{-3}$ and $UO_2F_6^{-4}$. Figure 15 shows a potentiometric titration of a uranyl sulfate solution with sodium fluoride. The first break in the curve occurs where approximately 7.5 millimoles of fluoride ion combine with 1.5 millimoles of UO_2^{+2} giving $UO_2F_5^{-4}$. The second break occurs where approximately 9 millimoles of fluoride ion have united with 1.5 millimoles of UO_2^{+2} giving $UO_2F_6^{-4}$. $UO_2F_3^{-1}$ and $UO_2F_4^{-2}$ may form at lower fluoride ion concentrations and lower pH values. Since this work is concerned with solutions above pH 5 these ions have not been investigated.

A solution of $UO_2F_6^{-4}$ is stable up to pH 6.70 at 25° C. Above pH

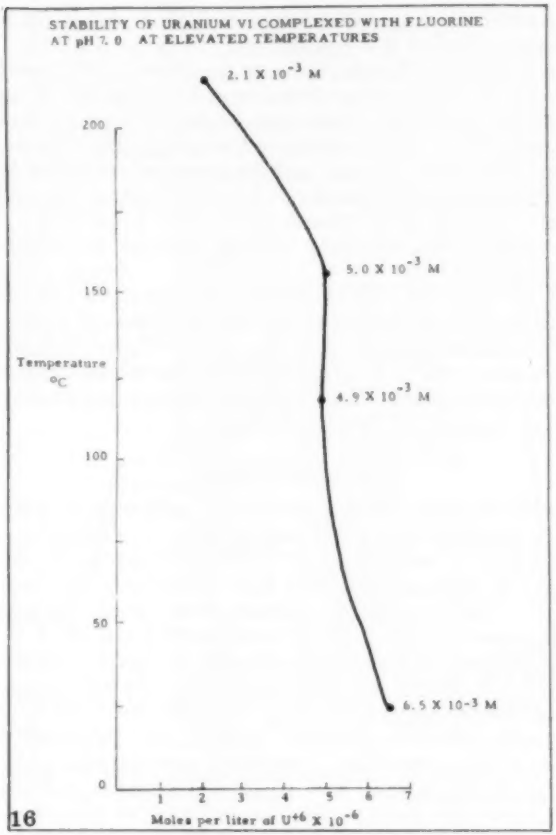


FIG. 16. Stability of uranium VI complexed with fluorine at pH 7.0 at elevated temperatures.

6.70 $UO_2F_6^{-4}$ converts to UO_2OH^+. UO_2OH^{+1} was identified by its absorption spectra peak at 3350° A and 4290° A (Fig. 1). Uranyl hydroxide precipitates at pH 7 as $UO_2(OH)_2.xH_2O$. The composition of this compound may be determined from Figure 15 since approximately 3 millimoles of OH^- combine with 1.5 millimoles of the uranyl ion. The concentration of UO_2OH^+ at pH 7.0 is 6.5×10^{-3} M at 25° C in the presence of the fluoride ion. The presence of the fluoride ion, therefore, increases the stability range of the uranyl hydroxide ion from 4.0×10^{-5} M to 6.5×10^{-3} M at pH 7.

At elevated temperatures the uranyl fluoride ion becomes slightly less stable. Figure 16 is a plot of the concentration of $UO_2F_6^{-4}$ against tem-

perature at pH 7.0. At a temperature of 215° C and a pH of 6.50, the concentration of $UO_2F_6^{-4}$ is 2.1×10^{-3} M.

$UO_2F_6^{-4}$ solutions will precipitate as pitchblende after reduction with either H_2S, SO_2 or H_2 at temperatures from 50° C to 300° C and between pH 2 and pH 7. Hydrogen sulfide reacts with $UO_2F_6^{-4}$ at room temperature to form a green UF_4. The solubility of this precipitate is below 10^{-6} M at 25° C. The uranium in solution and the green precipitate of UF_4 convert to brown pitchblende upon heating. As in the case of the carbonate ion the solution is blue at temperatures above 100° C, although clear below this temperature. The solubility of the uranium in solution remains below 10^{-6} M.

The UF_4 precipitated at 25° C consists of a grayish green acicular mass with thin plates of hexagonal crystals which are iridescent blues and greens. The pitchblende precipitated from the uranyl fluoride-sulfur system at temperatures above 100° C is a black earthy material with minute amounts of small iridescent crystals (UF_4?) and small transparent plates (S?). The pitchblende is composed of large crystallites.

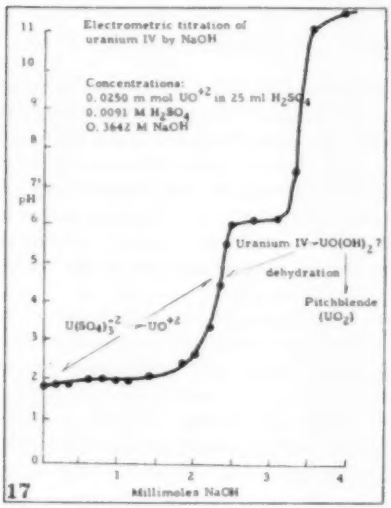
THE URANOUS ION

Tetravalent uranium forms green ions in sulfate acid solutions. The probable compositions are UO^{+2} and $U(SO_4)_3^{-2}$. These ions have an absorption peak at a wave length of 6,700 angstrom units. This permits determination of their concentration from mixtures of uranium (IV) and uranium (VI). The uranous ion oxidizes to the uranyl ion within twelve hours in the presence of air at 25° C between pH 1 and pH 7.

Uranium (IV) in an acid sulfate solution is predominantly $U(SO_4)_4^{-4}$ and $U(SO_4)_3^{-2}$ (30, p. 13). At pH 2.2 and 25° C the ions become unstable and black $UO(OH)_2$ precipitates (Fig. 17). The solubility of uranium in equilibrium with $UO(OH)_2$ decreases to 6.0×10^{-3} M at pH 4.62. The stoichiometry of the curve (Fig. 17) indicates a composition of $UO(OH)_2$ or $UO_2.xH_2O$ for the black precipitate. Aloy (1) stated that the composition is $UO_2.2H_2O$ and later Hiskey (14) thought it to be $UO_2.xH_2O$. In this current work the precipitate was dried at 25° C and analyzed by means of x-ray diffraction. The resulting pattern was identical with pitchblende (UO_2) although slightly diffused. Though not realized by Aloy and Hiskey the hydrated uranium dioxide loses its water of hydration upon drying and converts to anhydrous uranium dioxide (pitchblende). No improvement in crystallinity results from heating the synthetic UO_2 in the dry state. Hiskey found that partial oxidation to U_3O_8 takes place at 200° C. If, however, $UO(OH)_2$ in equilibrium with its solution is heated to 100° C or above, the hydrate loses all of its water and is converted to UO_2. This precipitate gives an excellent x-ray diffraction pattern for pitchblende.

The concentration of uranium in equilibrium with pitchblende at various temperatures and a pH value of 6.7 is given in Figure 18. Forty-eight hours were allowed for the system to come into equilibrium before making a solubility measurement. These solubility figures are too high and indicate the slowness with which uranium IV in the absence of sulfide ion will pre-

cipitate as pitchblende. When a solution of uranium IV reacts with hydroxide at pH 4.6 to form UO_2 the solubility of the UO_2 measured three months after the reaction is 6.0×10^{-3} M. At pH 8.5 it is 3.4×10^{-3} M. If these solutions are heated above 200° C the solubility of pitchblende is below 10^{-6} M and remains below this value after cooling the solution to 25° C. The effect of higher temperatures is probably to increase the approach to equilibrium. If this is true the solubility numbers of Figure 18 do not indicate the true solubility of pitchblende at a given temperature.



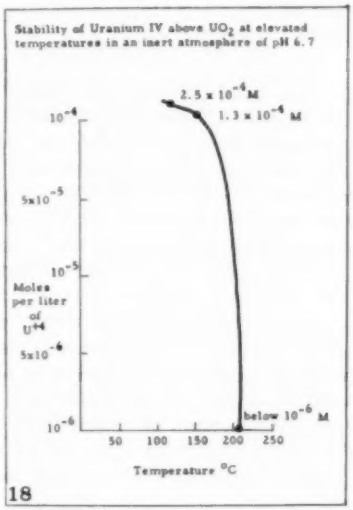

Stability of Uranium IV above UO_2 at elevated temperatures in an inert atmosphere of pH 6.7
2.5×10^{-4} M
1.3×10^{-4} M
Moles per liter of U^{+4}
below 10^{-6} M
Temperature °C
18

FIG. 17. Electrometric titration of uranium IV by NaOH.
FIG. 18. Stability of uranium IV above UO_2 at elevated temperatures in an inert atmosphere at pH 6.7.

The uranous ion solution when titrated with sodium carbonate does not form a complex with the carbonate ion as does the uranyl ion but precipitates as $UO_2.H_2O$. The dehydration and temperature effects are identical as in the discussion of the sodium hydroxide titration.

When solutions of uranous ion with sulfate are titrated with sodium fluoride at 25° C a soluble fluoride complex forms which is stable to pH 4.0. Present data indicate that the composition of this complex might be UF_2^{+2}. Above pH 4.0, green UF_4 precipitates. This compound is identical to the UF_4 previously mentioned when $UO_2F_6^{-4}$ reacted with H_2S.

The composition of the soluble uranium fluoride complex, UF_2^{+2}, may be an oversimplification. Katz and Rabinowitch (16, p. 359) think the complex might be $U(SO_4)_2F_2^{-2}$, which decomposes into UF_4 and $U(SO_4)_2$. At the high hydrogen ion concentration at which Katz and Rabinowitch considers this complex one may expect sulfate complexing (22, p. 301).

At higher hydroxide concentration, UF_2^{+2} might be the stable complex form.

The concentration of uranium in equilibrium with UF_4 at pH 5.90 and 25° C is 8.8×10^{-5} M. When a solution of UF_4 in equilibrium with uranium IV is heated to 180° C in an inert atmosphere there is no conversion of UF_4 to UO_2, since X-ray powder patterns of unheated and baked UF_4 agree.

The sulfide ion has no appreciable effect on the uranous ion stability in solution other than to prevent its oxidation. The phosphate ion decreases uranium (IV) concentration above pH 3. The concentration is less than 10^{-5} M.

THE EFFECT OF FOREIGN CATIONS ON URANIUM COMPLEXES

It is undetermined just how foreign cations might effect the stability of the uranium complexes discussed in this section. Experiments could be easily designed to test this, but the time involved is beyond the scope of this program. It has long been known that sodium forms a diuranate with uranium in alkaline solution (31), but the diuranate has been shown in this report to be quite soluble under certain conditions. Barium forms a relatively insoluble precipitate, $Ba_4UO_2(CO_3)_3$, with the uranyl carbonate complex (12), and UF_4 is oxidized to uranyl compounds by ferric oxide (30, p. 8).

The scope of the chemistry that has been completed on the reactions of cations with uranium generally lies beyond the range that is useful to the geologist. This is because the experiments have been performed under extreme conditions of temperature (ex. fusion at red heat), pH (ex. pH1), and foreign anion concentration (ex. oxalate solutions). There is little more that can be said about the relationship of uranium and pitchblende in ore-forming solutions until further work has been completed on cation effects.

THE ROLE OF PRESSURE IN PITCHBLENDE SYNTHESIS

Several experiments were completed on the effect of pressures up to 5,000 pounds per inch square in the synthesis of pitchblende. Uranyl carbonate, hydroxide, and fluoride solutions at a pH near 7 and at various pressures and temperatures in a hydrogen sulfide atmosphere were tested in the high pressure chamber illustrated in Figure 4. The effects recorded are necessarily those remaining after the system had returned to room temperature and pressure. Therefore only an approximation can be made as to what actually happens at elevated pressures.

The results indicate that for small amounts of H_2S at the same temperature more pitchblende was precipitated at higher pressure than at lower pressure. This would be expected since the solubility of hydrogen sulfide in solution increases with pressure and therefore there would be more sulfide ion available to react with the uranium ions at higher pressures.

The writer would infer that the role of pressure in the synthesis of pitchblende is essentially to keep the system closed and increase the solubility of the available gases.

SUMMARY

There are five uranium complex ions which conceivably might occur in natural solutions of pH 7 and at 25° C. They are listed below in order of decreasing stability.

Uranium ions in aqueous solutions	*Solubility at 25° C and pH 7*
1. Uranyl carbonate $(UO_2(CO_3)_3)^{-4}$	above 10^{-2} M
2. Uranyl pyrophosphate $(UO_2P_2O_7)^{-2}$	above 10^{-2} M
3. Uranyl fluoride $(UO_2F_6)^{-4}$	6.5×10^{-3} M
4. Uranous hydroxide $(UO(OH)^{+1}$	3.0×10^{-3} M
5. Uranyl hydroxide $(UO_2OH)^{+1}$	2×10^{-5} M

At elevated temperatures these uranium ions become less stable and the order of solubility is changed. They are listed below in order of decreasing solubility at 215° C near a pH of 7.

Uranium ions in aqueous solutions	*Solubility at 215° C and pH 7*
1. Uranyl fluoride	2.1×10^{-3} M
2. Uranyl hydroxide	1.5×10^{-4} M
3. Uranyl carbonate	9.5×10^{-5} M
4. Uranous hydroxide	below 10^{-6} M
5. Uranyl pyrophosphate	unknown

At 25° C and near pH 7 the uranyl carbonate, hydroxide, and pyrophosphate will react with sulfide to precipitate pitchblende which has a very small crystallite size. The concentration of uranium in solution when either the uranyl carbonate or hydroxide reacts with the sulfide ion is less than 10^{-6} M. The uranyl pyrophosphate reaction with sulfide has been only qualitatively investigated. Uranyl fluoride reacts with the sulfide ion at 25° C to precipitate uranium tetrafluoride, UF_4. The uranium in solution above UF_4 is less than 10^{-6} M. The sulfide ion has no effect on the solubility of uranium IV in solution other than to assist in keeping it in its reduced state. The hydroxide ion, however, reacts with uranium IV at 25° C near pH 7 to precipitate pitchblende. It has a very small crystallite size.

At the elevated temperature of 215° C and near pH 7 uranyl carbonate, hydroxide, fluoride, and pyrophosphate react with sulfide, sulfite, and hydrogen gas to precipitate pitchblende which has a large crystallite size. The concentration of uranium in solution above the pitchblende is less than 10^{-6} M, when sulfide ions react with uranyl carbonate, hydroxide and fluoride at 215° C. Uranium IV in an inert or H_2S atmosphere at 215° C and near pH 7 reacts with water to precipitate pitchblende. It has a large crystallite size. The concentration of uranium in solution above the pitchblende is less than 10^{-6} M.

Foreign cations are known to react with complex uranium ions and form precipitates. They will also change the chemical properties of solutions,

especially pH, and therefore have an effect on the stability of the uranium ions. There is a need for experimental investigation of cation reactions with uranium complexes.

Pressures up to 5,000 pounds per square inch have little effect on the stability of the uranium ions studied, other than to keep the system closed and increase the solubility of the gases in solution.

It is suggested that uranium in natural ore-forming solutions on the Colorado Plateau traveled in the hexavalent state. In the White Canyon pitchblende district the uranium probably moved through the sediments in aqueous solutions as a uranyl carbonate ($UO_2(CO_3)_3^{-4}$) or uranyl hydroxide ($UO_2(OH)^{+1}$) complex ion. These uranium ions were absorbed by the anthraxylon or attritus material and reacted with the organic sulfur within the cell walls or the pyritic sulfur within the interior of the cell to precipitate as pitchblende. Pitchblende not directly associated with organic matter probably precipitated due to the reaction of uranyl ions with pyrite or hydrogen sulfide. The temperature of these reactions may have been between 25° C and 260° C. It is suggested that all of the sulfide is genetically related to the organic matter and controls the precipitation of pitchblende.

It is inherently difficult to bridge the gap between laboratory and field relationships in mineral study. This is because we seldom know all the variables that are involved in ion transport and mineral precipitation. The variables that are known to exist are commonly difficult to reproduce in the laboratory. If, however, fundamentals concerning the chemical compounds that form the mineral systems, although seemingly far removed from the field, can be determined, then approximations to the conditions of mineral emplacement may be made.

It is hoped that the observations concerning the precipitation of pitchblende discussed in this paper may add further knowledge on pitchblende genesis.

Ecstall Mining Co., Ltd.,
Toronto, Ontario,
Dec. 5, 1957

REFERENCES

1. Aloy, J., 1899, Soc. Chim. France Bull. 3, 21, p. 613.
2. Arfvedson, J. A., 1824, Contribution toward a closer knowledge of uranium: Annalen der Physik et der Chemie (Poggendorf), v. 1, p. 245.
3. Bastin, E. S., and Hill, J. M., 1917, Economic geology of Gilpin Co. and adjacent parts of Clear Creek and Boulder Cos., Colorado: U. S. Geol. Survey Prof. Paper 94.
4. Cady, G. H., 1942, Concepts of physical constitution of coal: Jour. Geology, v. 50, p. 353.
5. Croft, W. J., 1953, An X-ray study of uraninite: Ann. N. Y. Acad. Sci., v. 62, Art. 20, p. 449–502.
6. Ebelman, J. J., 1842, Research on several compounds of uranium: Annalen der Chemie, v. 43, p. 286.
7. Furman, N. H., and Watters, J. I., 1950, Electrometric methods. Analytical Chemistry of the Manhattan Project: McGraw-Hill Book Co., Inc., New York.
8. Garrels, R. M., 1955, Some thermodynamic relations among the uranium oxides and their relation to the oxidation states of the uranium ores of the Colorado Plateau: Am. Mineralogist, v. 40, p. 1004–1021.
9. Gruner, J. W., 1952, New data of synthesis of uranium minerals: A.E.C. Annual Rept., June 1952, RMO-983, Part 1.
10. Gruner, J. W., 1956, Concentration of uranium in sediments by multiple migration accretion: Econ. Geol., v. 51, no. 6, p. 495–520.

11. Harned, H. S., et al., 1944, A.E.C. Yale Univ. Rept. for July, 1944.
Harvey, H. S., et al., 1944, A.E.C. Yale University Report for July.
12. Hedvall, J., 1925, Zeitschr. anorg. Chemie, v. 146, p. 225.
13. Hillebrand, W. F., 1893, The preparation and specific gravity of crystallized uranium dioxide: U. S. Geol. Survey Bull. 113, p. 37.
14. Hiskey, C. F., 1943, A.E.C. Rept. A-123, August 1943.
15. Ipatieff, V. N., and Muromtsev, B., 1930, Berichte der deutschen chemischen Gesellschaft, v. 63, p. 164.
16. Katz, J. J., and Rabinowitch, E., 1951, The Chemistry of Uranium: McGraw-Hill Book Co., Inc., New York, 609 pp.
17. Kerr, P. F., Brophy, G. P., Dahl, H. M., Green, J., and Woolard, L. E., 1957, Marysvale, Utah, Uranium area. Geol. Soc. Amer.: A.E.C. Special Paper 64, 203 p.
18. Kerr, P. F., 1950, Mineralogical studies of uraninite and uraninite-bearing deposits: A.E.C. Interim Tech. Rept.
19. Kessler, L., 1857, Procedure for the preparation and analysis of Uranium oxide: Jour. Pharm. Chim., v. 31, p. 182.
20. Kunin, R., 1945, A.E.C. Rept. A-3254, May, 1945.
21. Long, S. M., 1953, An annotated bibliography of selected references on the solid-state reactions of the uranium oxides: Nat. Bur. Standards Circ. 535, p. 1–95.
22. Latimer, W. M., 1952, Oxidation Potentials: Prentice Hall, Inc., New York, p. 300–304, 2nd Ed.
23. MacInnes, D. A., and Longsworth, D. A., 1942, A.E.C. Rept. A-380, November, 1942.
24. Miller, L. J., 1955, Uranium ore controls of the Happy Jack Mine, White Canyon, Utah: Econ. Geol., v. 50, no. 2, p. 159.
25. ——, 1954, Progress report on the chemical environment of pitchblende: A.E.C. Annual Rept., June 1954, RNE-3096, Part 2.
Morey, A., 1953, New method of hydrothermal synthesis: Amer. Ceramic Soc., 36.
26. Oechsner de Connick, F. W., 1908, Uranium compounds: Bull. de la Classe des Sciences, Acad. Royale de Belgique, 992.
27. Pascal, P., 1913, Stabilities of uranium hydrophosphate and pyrophosphate: Soc. Chim. France Bull., v. 13, p. 1089–1103.
28. Pisani, F., 1861, Comptes Rendus, v. 52, p. 106.
29. Price, T. D., and Huffman, E. H., 1943, A.E.C. Rept. Chem. s-208, October.
30. Rodden, C. J., 1950, Analytical Chemistry of the Manhattan Project: McGraw-Hill Book Co., Inc., New York.
31. Wilder, C. D., 1943, A.E.C. Rept. Chem. s-313, August.
32. Wöhler, F., von, 1842, Preparation of uranium: Annalen der Chemie, v. 41, p. 345.

Economic Geology
Vol. 53, 1958, pp. 546–562

THE GEOLOGY AND METAMORPHISM OF THE NAIRNE PYRITIC FORMATION, A SEDIMENTARY SULFIDE DEPOSIT IN SOUTH AUSTRALIA

BRIAN J. SKINNER

ABSTRACT

The Nairne Pyritic Formation is the basal formation of the Kanmantoo Group, a vast thickness of fine-grained graywackes, quartzites and siltstones. The sulfide-bearing graywackes and siltstones contain pyrite and pyrrhotite to a maximum of 15 percent of the rock by volume. They are believed to be original deep-water sulfide-bearing marine sediments. There are two major pyritic members, generally from 50 to 100 feet thick, which outcrop over a minimum distance of 65 miles.

Metamorphism has developed two major mineral assemblages, quartz-muscovite-albite-(andalusite-kyanite)-pyrite-pyrrhotite, and quartz-muscovite-albite-microcline-pyrite-pyrrhotite, which coexist and are interbedded. The composition of muscovite in both assemblages and of microcline and albite in the second assemblage have been determined and a phase diagram prepared. The pyrrhotite composition is $Fe_{0.907}S$ and a coexisting sphalerite contains 9.0 percent Fe and 2.3 percent Mn. It was not possible to estimate the temperature and pressure of metamorphism from the data available, although an attempt was made using pyrite-pyrrhotite and sphalerite-pyrrhotite and the experimental data of Arnold and of Kullerud.

GENERAL GEOLOGY

THE Nairne Pyritic Formation is a series of pyrite- and pyrrhotite-bearing graywackes and siltstones at the base of the Kanmantoo Group. The Kanmantoo rocks outcrop on the eastern side of the Mt. Lofty Ranges, South Australia (Fig. 1), and have been mapped and described by Sprigg et al (14, 16), by Kleeman and White (8) and Kleeman and Skinner (9). The age of the series is uncertain, but is considered to be Cambrian (15).

The Kanmantoo Group comprise at least 26,000 feet of very fine-grained quartzites, graywackes and siltstones. Bedding in the quartzites is poorly defined, but in the graywackes and siltstones is generally clearly marked by composition and grain size differences. Throughout the Kanmantoo Group small scale cross-bedding, poorly defined graded bedding, sedimentary slump structures and other markings interpreted as scour channels and flute castings (10) can be found.

The Nairne Pyritic Formation has been proposed as the base of the Kanmantoo Group (9). It forms a convenient marker horizon in an otherwise monotonous sequence but certainly does not represent a break in sedimentation. Below the Nairne Pyritic Formation is a fine-grained graywacke. The graywacke grades down into a massive, strongly cross-bedded quartzite, at least 2,000 feet thick.

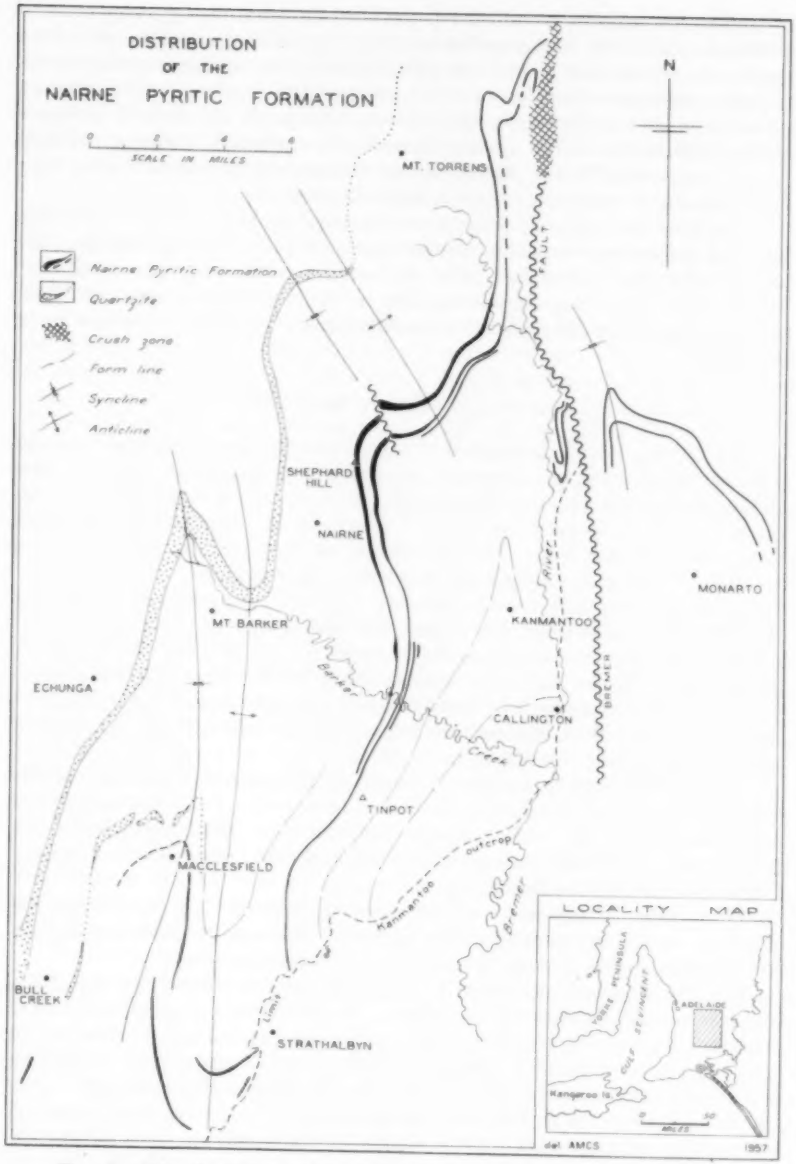


FIG. 1. Distribution of the Nairne Pyritic Horizon, South Australia.

Below the massive cross-bedded quartzite are additional graywackes and siltstones, but they are interbedded with increasing amounts of coarse quartzites, arkose, and limited calc-cilicate beds. At no stage can any break in sedimentation be seen but the evidence suggests that the pyritic horizons occur at, or slightly above, a point marking a change in the mode of sedimentation. Below the Nairne Pyritic Formation is a mixture of coarse and fine, largely quartz-rich beds. Above the formation is a vast thickness of very fine-grained graywackes, quartzites, and siltstones.

The Kanmantoo Group have been subjected to regional metamorphism. Detailed studies have not been completed, but it is readily apparent that the metamorphic grade increases from the south-west towards the north-east. Much of the area of good outcrop lies in the quartz-andalusite-muscovite-plagioclase grade, but in places a quartz-sillimanite-orthoclase-plagioclase grade is reached.

THE NAIRNE PYRITIC FORMATION

The Nairne Pyritic Formation is a stratigraphic name describing several sulfide-bearing members, separated by sulfide-free graywackes, at the base of the Kanmantoo Group. The pyritic beds, which form conspicuous outcrops, have been mapped for a strike length of 65 miles and are certainly more extensive than this. The persistence and excellence of outcrop makes the Nairne Pyritic Formation an excellent marker horizon.

There are two major sulfide-bearing members, separated by 1,500 feet of sulfide-free graywackes and quartzites, which vary in thickness from 6 inches to 400 feet, but are generally between 50 and 100 feet thick. Three smaller, more limited members occur stratigraphically above the main units. They are rarely more than 10 feet thick and average about 3 feet. The discontinuity of the minor members, as mapped in the field, is partly due to poor outcrop and partly to lensing of the sediments.

Each sulfide-bearing member is made up of many thin-bedded, sulfide-rich graywackes and siltstones. Individual beds within a member range from 1 inch to 10 feet thick. In common with the other Kanmantoo rocks, the pyritic beds are very fine-grained quartz-rich rocks, and the presence of sulfides is their only distinctive feature.

The sulfide-bearing rocks are all distinctly bedded, and the sulfides are obviously strung out parallel to the bedding. The sulfide-bearing rocks are always conformable, and never cross-cut the bedding planes.

The amount of sulfide within a member is remarkably constant along the strike except where the beds pinch out. From bed to bed within a member there is a variation of 1 to 15 percent sulfides by volume, but the member as a whole averages about 10 percent sulfide. Where the pyritic formations lens down or pinch out, they become finer grained and increasingly more micaceous. With the increase in mica there is a reduction in sulfide content, but the formations remain visibly sulfide bearing until the final pinch out. The stratigraphically lowest pyritic member lenses out near Tinpot (Fig. 1). This member thins from a thickness of 200 feet to nothing over a distance

of three-quarters of a mile. It is definitely a sedimentary thinning and lensing and not a misleading effect created by a tailing out of the sulfides in a continuous horizon, because individual beds within the member can be shown to lens out gradually. This lowest pyritic member has not been observed south of Tinpot. In the anticline west of Strathalbyn there are two distinct pyritic horizons. However, the lowest horizon here cannot definitely be connected with the pyritic horizon that lenses out near Tinpot.

Unfortunately the pyritic beds weather rapidly, forming a resistant limonite-quartz-kaolin gossan. Pyrrhotite disappears rapidly and has not been observed in outcrop. Pyrite is more resistant and is often found as residuals enclosed in a limonite-iron sulfate halo. The acid sulfate solutions released during weathering rapidly alter the silicate minerals present.

Three miles north of Nairne, at Shephard Hill, a large quarry is operated for the recovery of the sulfides for their sulfur content. The quarry, in the stratigraphically lowest pyritic member that outcrops continuously for 30 miles north of Tinpot, affords an excellent opportunity for examining a continuous section of fresh, unaltered material. In no other place can such fresh material be obtained. All specimens obtained from surface outcrops showed sufficient alteration to render accurate mineralogical studies useless, and detailed work on the mineralogy has therefore been limited to specimens from the quarry.

COMPOSITION OF THE PYRITIC SEDIMENTS

All the beds in the pyritic formation are quartz-rich and all contain sulfides. Although individual beds may be classified as quartzites, graywackes or siltstones, the mineralogy is limited to a few assemblages. 65 percent of the host rock is a quartz-muscovite-albite-microcline assemblage. 25 to 30 percent is a quartz-muscovite-albite-(andalusite, kyanite) assemblage. The remainder, occurring in beds less than 1 foot thick, is quartz-biotite-albite-microcline, quartz-muscovite-scapolite-plagioclase or quartz-biotite-spessartite-feldspar assemblages.

The present mineralogy must reflect the initial ratio of mica and clay minerals to feldspars. The quartz-muscovite-albite-(andalusite, kyanite) asemblage is derived from the most micaceous and clay-rich initial sediments and contains only 35 to 45 percent free quartz. The quartz-muscovite-albite-microcline assemblage contains from 45 to 60 percent free quartz.

Sedimentary banding throughout the pyritic horizons is well defined, both macroscopically and microscopically, by differences in composition and grain size. Compositional variations are generally expressed by variations in the ratio of quartz to micas and bear little relation to grain size, except that highly micaceous rocks contain the finest quartz grains and were presumably the finest grained initial sediments. Beds range in width from 1 inch to 10 feet, and individual beds are uniform in grain size, the coarser ones having grains up to 0.5 mm in diameter and the finer beds containing grains down to 0.03 mm in diameter. Coarse beds are rare and the average grain size is 0.1 mm. An estimated 5 percent of the beds show graded bedding (Fig. 2).

The perfection of sorting varies somewhat and the graded units range from 1 cm to 4 cm thick and have a grain size range from 0.2 mm to 0.03 mm.

The sulfides have the same grain size as the silicates, being coarse in the coarse sediments and fine in the fine-grained sediments. In graded beds this grain size relation was particularly noticed (Fig. 2). There is a tendency for coarse pyrite grains to be concentrated at the base of graded beds, but the effect is not pronounced. The only significant concentration of sulfides occurs in

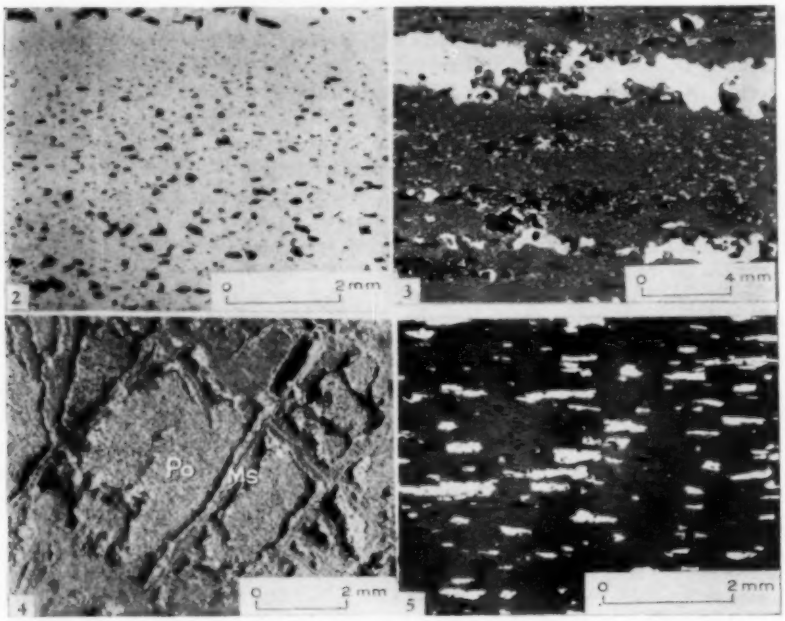


FIG. 2. Graded bedding in a pyrite- and pyrrhotite-bearing graywacke, Nairne Pyrite Horizon. Transmitted light. Black grains are sulfides.

FIG. 3. Bands of concentrated pyrite with fine disseminated pyrite and pyrrhotite between them. Reflected light.

FIG. 4. Secondary alteration of pyrrhotite (Po) to pyrite and marcasite (Ms). Polished surface. Oblique illumination.

FIG. 5. Elongate pyrrhotite grains, flattened parallel to the foliation. Reflected light. White is pyrrhotite.

some of the coarser grained rocks, which contain bands of practically pure pyrite up to 1 cm wide. The pyrite layers are parallel to the bedding and are spaced at intervals of 0.5 cm to 5.0 cm, with fine-grained pyrite and pyrrhotite disseminated through the silicates between them (Fig. 3). Laterally the pyrite bands die out within a few feet, and are generally no more than a foot long. Where the beds show no concentration, the sulfides occur as discrete grains uniformly distributed through the silicates.

Within any particular pyritic member, pyrite and pyrrhotite are present in roughly equal amounts, though the proportion of one to the other varies widely from bed to bed within the member. Minor amounts of sphalerite and chalcopyrite with traces of galena and arsenopyrite are also present. A small amount of rutile is intergrown with the sulfides and with the silicates.

Pyrite predominates in coarse grained beds and pyrrhotite in the very fine-grained and highly micaceous beds. Within the concentrated pyrite layers there may be small crystals of pyrrhotite. These always occur in lines parallel to the bedding and suggest that even slight variations in the sulfide composition of the original sediments have been preserved.

Oxidation and secondary alterations are widespread and if not recognized can lead to misunderstandings. The alterations are concentrated around shears, joints, and fractures providing access for surface waters. The effects decrease rapidly with depth but have been noticed even on the deepest levels of the Shephard Hill quarry and in an adit under Shephard Hill. Below the level of complete oxidation one finds extensive alteration of pyrrhotite to marcasite and in places to pyrite (Fig. 4). In polished section the secondary sulfide often appears colloform. In hand specimen it is easy to recognize secondary sulfide alterations because the secondary mineral encrusts or forms veins in remnants of the pyrrhotite or may even grow as minute crystals on the walls of the cavity left by removal of the pyrrhotite. Secondary sulfate minerals may be associated with secondary marcasite and pyrite, making it difficult to prepare good polished sections.

Another common secondary effect below the oxidation zone is the development of minor veins and crusts of sulfates and clays. In thin section these veins are confusing as they are fine grained and have a high birefringence resembling carbonates in appearance. Edwards (4) gave a brief description of the mineralogy of the Nairne Pyritic Formation and mentioned small carbonate veins. In the present study no carbonates were found.

All secondary effects are readily apparent, not only from their mineralogy, but also from their obvious relation to the surface and their concentration near shears and joints that have provided access for sulfate-rich surface waters.

METAMORPHISM OF THE NAIRNE PYRITIC FORMATION

The mineralogy and relations between minerals in the pyritic beds are most interesting. It is believed that compositional variations in the beds accurately reflect variations in the initial sediments. The present mineralogy and texture of the rocks however, were developed in response to metamorphism.

Sedimentary features are preserved, even on the finest scale. Therefore, it is unlikely that much movement, or redistribution of material occurred within the beds during metamorphism. There is very little tectonic deformation within the pyritic horizons, but minor joints, tension fractures, small shears and, more rarely, boudinage structures, do occur. No movement has occurred on most of the shears, though offsets of a few inches are sometimes found. All fractures are limited in length, commonly being confined to one bed. Highly quartzose beds develop fractures more readily than highly micaceous beds.

The minor breaks within the pyritic horizons have provided loci for cross-cutting veins and segregations of sulfides and silicates. The veins are always narrow, generally less than 1 cm wide. Like the minor breaks in which they develop, the veins are limited in extent; a single large hand specimen may contain the entire vein or segregation.

The mineralogy of the veins and segregations strongly reflects the mineralogy of the wall rock. Thus, tension joints in quartz-scapolite-muscovite-pyrrhotite beds are invariably sealed with coarse crystals of scapolite, quartz and pyrrhotite, but fractures in adjacent quartz-muscovite-microcline-albite-pyrite-pyrrhotite beds are sealed with coarse microcline, quartz and muscovite. The bulk compositions of the segregations may differ from the enclosing rock, but the individual mineral compositions are identical.

The close relation between the mineralogy of the wall rocks and veins and the limited extent of the veins, suggests that the veins were formed as metamorphic segregations. A minute percentage of the total rock volume is involved in the veins and segregations. A small amount of chemical movement must have occurred to form the veins, but the amount involved is so small that it would not, in any way, alter the bulk composition of the beds.

Texture

All beds in the pyritic formation have a well developed foliation. In the Shephard Hill quarry, this foliation is parallel to the bedding and roughly parallel to the axial plane of the regional folding.

The foliation is expressed by strongly oriented and elongate micas having their (001) plane parallel to the foliation. Pyrite and pyrrhotite grains are in places flattened parallel to the foliation (Fig. 5). The sulfide elongation is marked in the highly micaceous beds but is not present at all in mica-free layers. Where elongation of the sulfide grains occurs, both pyrite and pyrrhotite have a preferred crystallographic orientation. Where elongation is absent, the sulfides have a random crystallographic orientation.

The elongation of pyrite is parallel to the cube face. From the concurrent extinction of the elongated pyrrhotite grains in polarized light it is obvious that pyrrhotite has a strongly preferred crystallographic orientation. The relation of the pyrrhotite crystal lattice to the foliation could not be determined. Some pyrrhotites appear to have grown as epitaxic growths on, and even in, muscovite books. In this case optics suggest, but do not prove, that the common growth planes are the muscovite (001) and pyrrhotite (0001).

The perfection of lineation shown by the sulfides depends on the amount of mica present. The higher the mica content, the more strongly developed the sulfide lineation. This suggests that the pyrite and pyrrhotite orientation in highly micaceous beds is a growth effect controlled by the mica orientation rather than by the external stresses acting on the pyrite and pyrrhotite lattices. Pyrite and pyrrhotite do not replace the mica and the texture appears to be one developed between compatible minerals.

The growth relations between the sulfide minerals suggest that pyrite and pyrrhotite are completely compatible. The strong cross-cutting relations,

reactions and alterations common in many sulfide deposits are absent. The only alterations present are demonstrably secondary and related to weathering, as previously discussed.

Textural relations suggest that the sulfides and silicates, as observed today, have developed together. It is believed that the only essential difference between the present and original rock compositions is a reduction in water content. Thus, unless affected by secondary alterations, all the minerals present in the pyritic beds have compositions developed in response to the same metamorphic conditions.

Mineralogy

The mineralogical composition of the pyritic host rock is rather uniform. As previously stated, there are few mineral assemblages, the two major ones being quartz-muscovite-albite-microcline and quartz-muscovite-albite-(andalusite, kyanite). The amount of each mineral in an assemblage varies widely.

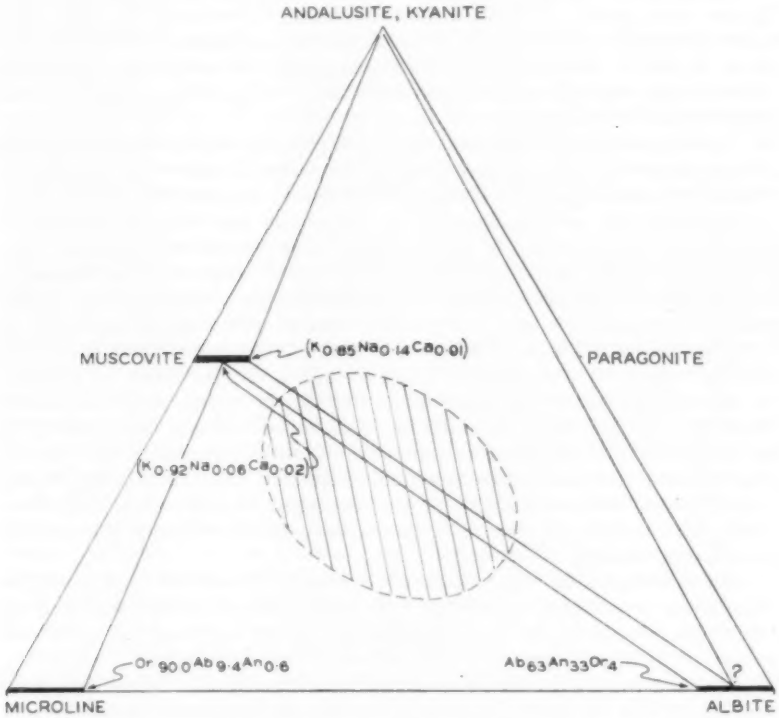


FIG. 6. Metamorphic assemblages and mineral compositions in Nairne Pyritic Horizon, Shephard Hill. Shaded area is the estimated composition range of the Shephard Hill rocks.

The range has been visually estimated and plotted in Figure 6 together with the phase assemblage boundaries postulated for the observed assemblages. The diagram is for assemblages with an excess of quartz and of iron sulfides, none of which could be plotted.

Quartz-Muscovite-Albite-(Andalusite, Kyanite)-pyrite-pyrrhotite.—Kyanite and andalusite are present in equal amounts. They are not intimately intergrown and mineral separations yield clean fractions of each. Thin sections do not reveal any evidence of replacement or alteration from one to the other. One is forced to conclude that they are a stable pair and that metamorphism in the area of the Shephard Hill quarry occurred at, or near, the andalusite-kyanite transition.

Muscovite, the only mica present, has been separated and analysed for K and Na by flame photometer and for Ca by titration. If we assume an ideal Al/Si ratio for the muscovite, a formula of $(K_{0.85}Na_{0.14}Ca_{0.01})Al_2(Si_3Al)O_{10}(OH)_2$ is indicated.

X-ray measurement of the (006) and (00,10) planes of the muscovite give a value for c_o of 19.962 ± 0.008Å. Using Yoder and Eugster's (15) value of 20.097 ± 0.05Å for c_o of pure muscovite, Eugster and Yoder's (6) value of 19.15Å for c_o of pure, natural paragonite, and assuming c_o to change linearly with composition, gives a composition of $(K_{0.86}Na_{0.14})Al_2(Si_3Al)O_{10}(OH)_2$ for the muscovite.

The agreement between analysis and physical measurement is surely fortuitous, for many unestimated effects may cause errors. The presence of Fe and Mg was ignored. Optical measurement suggests that Fe, at least, is negligible, but without analysis one cannot be sure. Small amounts of albite may have remained in the muscovite after separation. Optical examination of the final muscovite fraction showed much quartz as impurity and it is quite possible that a few grains of untwinned albite escaped notice. X-ray powder photos do not record any albite however, and if albite is present, it must be less than 3 to 4 percent of the total. It has been assumed that the muscovite has the ideal formula $(K,Na)Al_2(Si_3Al)O_{10}(OH)_2$. Variations in the Al content may be expected, especially in highly aluminous rocks. However, it is doubtful if the effect of Al variation on the c_o value is as large as the physical uncertainty of measurement. Finally, one must always beware of partial analysis, since one has no check on internal consistency of the results. The analyses, when repeated on at least two separate muscovites, were identical. The check with physical measurement indicates that, in this case at least, partial analysis is justified.

It was not possible to get a pure albite sample. Small flakes of muscovite were always intermixed, no matter how finely ground. The composition of the albite determined by the Michel-Levy method is $Ab_{60}An_{40}$. This, of course, gives no measure of the Or molecule in solid solution.

Quartz-Muscovite-Albite-Microcline-Pyrite-Pyrrhotite.—The muscovite in this assemblage, by partial analysis of two samples, has a composition of $(K_{0.92}Na_{0.06}Ca_{0.02})Al_2(Si_3Al)O_{10}(OH)_2$. The c_o value is 19.990 ± 0.008Å, which indicates a composition of $(K_{0.90}Na_{0.10})Al_2(Si_3Al)O_{10}(OH)_2$. This is again a satisfactory agreement and probably a more realistic one than the

previous case. The estimate is subject to the limitations previously outlined, but in this case the purity of the sample is definite. No feldspars or quartz were detected either optically or by X-rays.

Microcline and albite could not be satisfactorily separated. However, pure microcline from a small segregation in the same bed as one of the analysed muscovites had a composition, determined by partial analysis, of $Or_{90.0}Ab_{9.4}An_{0.6}$. The segregation containing the microcline was entirely confined to a small tension fracture within a single bed 2 feet thick. It is felt that this material satisfactorily establishes the microcline composition, since fine-grained muscovite and a little plagioclase and quartz were also present in the segregation.

Optically the microcline appears monoclinic and lacks the characteristic cross-hatched twinning. X-ray powder diffraction photographs however, show a smearing of the (130) and (131) reflections indicating a splitting of the lines due to triclinic symmetry.

It was not possible to get a pure albite sample that was demonstrably in equilibrium with microcline and muscovite. However, a specimen was obtained from a segregation found in loose quarry material. The host rock is indeterminate, but only quartz-microcline-albite-muscovite rocks could be found nearby. It is believed this albite indicates the approximate, if not the actual, composition of the plagioclase in the quartz-microcline-albite-muscovite assemblage. Partial analysis showed $Ab_{63}An_{33}Or_4$. The composition of the plagioclase, determined by the Michel-Levy method in thin section, is $Ab_{60}An_{40}$, which is the same as the albite in the quartz-muscovite-albite-(andalusite, kyanite) assemblage.

The experimental work of Eugster and Yoder (7) on the system potassium feldspar-albite-corundum-water indicates complete miscibility between the alkali feldspars at the upper stability limit (660–670° C) of paragonite at 2000 bars water pressure. Later work by Yoder et al. (19) however, indicates that at 2000 bars water pressure the crest of the alkali feldspar solvus is at 673° C, and that at 665° C, the estimated breakdown temperature of paragonite at 2000 bars water pressure, there would be an immiscibility gap of approximately 25 mol % Or. In the Shephard Hill rocks there is a very large immiscibility gap (approximately 86 mol % Or) between the feldspars, and paragonite is absent. Thus, before the temperature was high enough to give a single feldspar phase or even a narrow immiscibility region between the two feldspars, paragonite had broken down. This may be explained in several ways. Calcium produces a drastic rise in the alkali feldspar solvus (19) and hence, at a given temperature and pressure alkali feldspars containing calcium will have a wider immiscibility gap than the pure alkali feldspars. Secondly, by following the argument of Thompson (14), the partial water pressure is much lower than the total pressure during region metamorphism. Therefore paragonite, a hydrous mineral, will have a much lower breakdown temperature at a given total pressure than is observed in experimental work where the water pressure equals the total pressure. The alkali feldspar solvus, however, is affected only by the total pressure since the feldspar phases are anhydrous. Finally, in the experimental work referred to, the alkali feldspar

phases produced are the high forms while in the Shephard Hill rocks microcline, the 'low' form of potassium feldspar is found. The present study did not establish whether the plagioclase was a 'high' or 'low' form but it is considered almost certain to be a 'low' form. There is considerable doubt that synthetic studies on the 'high' feldspars are directly applicable to 'low' feldspars, but a consideration such as has been presented does point out that the metamorphism of the Nairne Pyritic Formation in the Shephard Hill area is most unlikely to have occurred at the high temperatures, above 600° C, discussed. This point is further substantiated by the extremely fine grain size of the rocks and one feels that the metamorphism must have occurred closer to 300° C than 600° C. In addition, at a depth of burial of 26,000–50,000 feet (see Temperature and Pressure of Metamorphism), a reasonable estimate of a geothermal gradient in quartz-rich rocks of 20° C/Km gives a temperature range of 170°–260° C.

Minor Rock Types.—The two preceding mineral assemblages account for 95 percent of the pyritic sediments. Small thicknesses of other rocks are present but have not been studied in detail. Of these quartz-scapolite-muscovite-plagioclase-pyrite-pyrrhotite beds are of interest. Always less than 1 foot thick, these beds behave competently and develop numerous tension fractures. The rock contains at least 50 to 60 percent free quartz, about 5 to 10 percent scapolite with muscovite and plagioclase forming the remainder. Plagioclase is present as fresh grains. Partial analysis showed the scapolite to be sodium-rich. The significance of the rock is puzzling. It appears to be a definite sedimentary bed, but the reason for scapolite developing is not clear.

Very small amounts of a quartz-biotite-feldspar-spessartite rock occur. The spessartite is concentrated in and around biotite, and contains approximately 35% MnO, as determined by X-ray fluorescent analysis. The only other assemblage recognized was quartz-muscovite-biotite-microcline-plagioclase but it is possible that other minor beds occur. The compositions of the coexisting silicates and the suggested phase relations between them, are plotted in Fig. 6.

Sulfide Minerals.—The sulfide mineral compositions have been studied in detail. Analyses of pyrite and pyrrhotite by the Department of Mines, South Australia, are presented in Table 1. Arnold (1) presented data relating pyrrhotite composition with the interplanar spacing of the (102) plane for a hexagonal cell. The measured values of $d_{(102)}$ and the estimated composi-

TABLE 1

CHEMICAL COMPOSITION AND UNIT CELL DATA FOR PYRITE AND PYRRHOTITE

No.	Fe%	S%	Insol%	Mol. % Fe	$d_{(102)}$ Å	Mol. % Fe (est.)
Pyrrhotite 1	60.8	38.8	0.1	47.3	2.0672±0.0008	47.35
Pyrrhotite 2	61.3	39.0	nil	47.4	2.0678±0.0008	47.35
Pyrite 1	46.4	52.9	1.0	33.5	a_0 5.4183±0.0007	—

tions from Arnold's data are also presented in Table 1. The agreement between analysis and physical measurement is excellent, and the formula of the pyrrhotite is established as $Fe_{0.947}S$.

Pyrite and pyrrhotite are a compatible pair of minerals and have been involved in the metamorphism of the Nairne Pyritic Formation. Therefore Arnold's (2, 3) data on the composition of coexisting pyrite and pyrrhotite at different temperatures may be used. The analysis and unit cell measurement of pyrite bear out Arnold's contention that pyrite does not show appreciable solid solution of FeS. Pyrrhotite containing 47.35 mol. % Fe is in equilibrium with pyrite at 275° C (3). The uncertainty in this estimate is not easily established, but errors of 0.05 mol. % Fe in the estimated pyrrhotite composition produce changes of 25° C in the equilibrium temperature. Pressure, at least up to 2,000 bars, does not have an appreciable effect on the equilibrium temperature determined.

There is considerable interest in the various symmetries and superstructures shown by pyrrhotite, so the X-ray powder diffraction data are presented

TABLE 2

X-RAY POWDER DIFFRACTION DATA FOR PYRRHOTITE ($Fe_{0.947}S$), FROM SHEPHARD HILL, SOUTH AUSTRALIA

CoKα radiation; 114.6 mm dia. camera; Cut off 14 Å; Visual estimation of intensities (I).

I	d Å	I	d Å	I	d Å	I	d Å
3	5.85	1	2.47	7	1.720	3	1.106
1	5.54	1	2.33	4	1.609	5	1.103
0.5	3.42	1	2.19	1	1.490	0.5	1.089
1	3.35	2	2.15	4	1.444	3	1.071
7	2.98	10	2.067	4	1.433	4	1.050
2	2.87	0.5	1.977	4	1.324	3	0.9950
0.5	2.81	0.5	1.907	3	1.294	3	0.9551
8	2.64	1	1.837	3	1.176	4	0.9108

in Table 2. Weak super lattice lines are present, but there is no tendency towards the line splitting observed with some monoclinic pyrrhotites.

Numerous measurements of pyrrhotites from different beds and different parts of the quarry failed to show any significant differences. Pyrite and pyrrhotite have constant composition regardless of the other minerals present.

Sphalerite is widespread in small amounts, generally intermixed with pyrrhotite. Polished sections show the sphalerite to be quite clean and not to contain exsolved pyrrhotite or chalcopyrite. Two sphalerites have been separated and analyzed. The data are presented in Table 3. The manganese content is surprisingly high considering the low manganese content of the beds. The only other manganese-bearing mineral found was spessartite, which is present as a minor mineral in a very poorly represented assemblage.

Kullerud's (11) data on the composition of ZnS in equilibrium with FeS at different temperatures is applicable for coexisting pyrrhotite and sphalerite. The sphalerite at the Shephard Hill quarry contains an average of 15.2 mol. % FeS. Kullerud's data show a formation temperature of 500° C at 1 bar

TABLE 3

CHEMICAL COMPOSITION AND UNIT CELL SIZE OF SPHALERITES IN EQUILIBRIUM WITH PYRRHOTITE

No.	Zn %	Fe %	Mn %	Cd %	Cu %	Mol. % FeS	a_0, Å
Sl. 1	55.1	9.0	2.3	0.19	<0.03	15.3	5.4250 ±0.0008
Sl. 2	55.0	8.8	2.5	0.18	<0.03	15.1	5.4242 ±0.0009

pressure, with a positive pressure effect of 30° C/1,000 bars. There is an error in Kullerud's conversion of wt. % to mol. % which displaces the solvus slightly. The error involved is approximately + 25° C at 500° C and has been included in the temperature estimate.

Temperature and Pressure of Metamorphism

The pyrite-pyrrhotite data and the sphalerite-pyrrhotite data have been presented graphically in Fig. 7. The intersection point of the two lines should give the temperature and pressure of metamorphism at the Shephard Hill Quarry. The negative pressure indicated is obviously ridiculous. Uncertainties of measurement have not been plotted. Even an uncertainty of ± 100° C in each estimate would not bring the data into reasonable agreement.

There were at least 26,000 feet of overlying sediments involved in the same metamorphism as the pyritic horizons. Thus, a minimum pressure of 2,500 bars must have been exerted on the pyritic sediments. Since the topmost beds in the stratigraphic section are also highly metamorphosed, this is definitely a minimum. If one postulates a doubling of the Kanmantoo sediments by folding one reaches a possible maximum of pressure, since no great thickness of later sediments have been laid on the Kanmantoo rocks. The structure of the Kanmantoo Series certainly does not suggest even a doubling of the sediments, so 5,000 bars is a reasonable maximum.

The use of solid solutions in two component systems such as pyrite-pyrrhotite and sphalerite-pyrrhotite to determine temperature and pressure of formation involves two major assumptions. The first assumption is that all phases present were at equilibrium under the metamorphic conditions. Examination of a large number of pyrite, pyrrhotite and sphalerite samples from Shephard Hill showed that they all have constant compositions. No evidence of disequilibrium can be found and it is felt that the first assumption is valid for both pyrite-pyrrhotite and sphalerite-pyrrhotite pairs.

The second assumption is that minor elements do not affect the solvus and hence invalidate the use of an experimentally determined solvus between pure components. In the case of pyrite-pyrrhotite this assumption seems to be valid since minor elements were not detected by standard analytic methods. For sphalerite-pyrrhotite the second assumption may not be valid because the sphalerite contains large amounts of Mn. Kullerud stated that MnS in small amounts did not affect the solubility of FeS in ZnS. 4 mol. % MnS in the Shephard Hill sphalerite is more than twice the quantity considered by Kul-

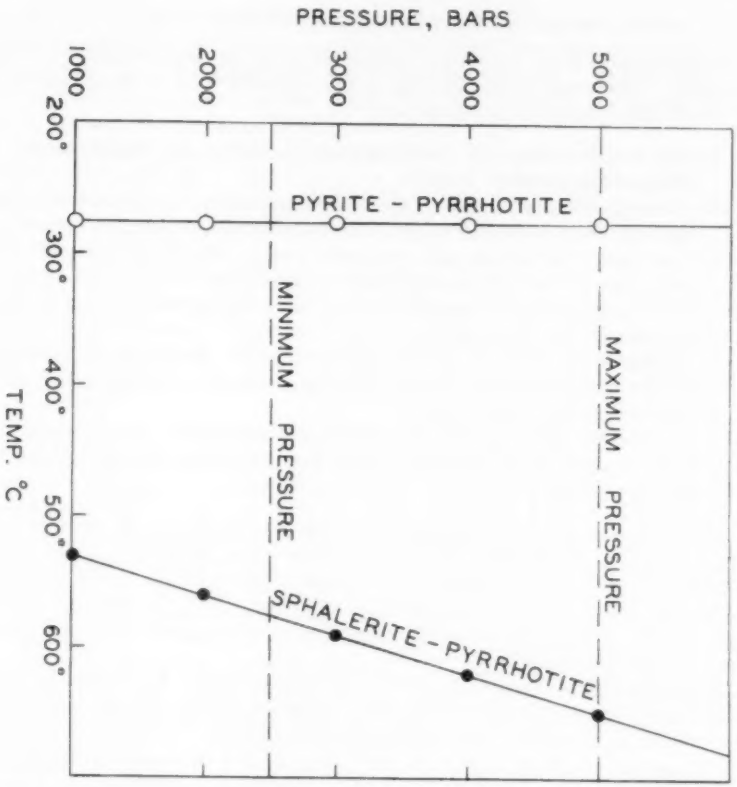


FIG. 7. Pressure-temperature graph for the pyrite-pyrrhotite and sphalerite-pyrrhotite solvus relations assuming ideal conditions.

lerud, and it is possible that his conclusion is not valid in this region. If MnS does, in fact, affect the FeS solubility, it apparently increases the amount of FeS entering the sphalerite structure. This would invalidate the use of Kullerud's ZnS-FeS solvus in this instance.

Further experimental work on the Al_2O_3-SiO_2 system may give the transition curve for the pair andalusite-kyanite.. The slope of this curve has already been estimated (14), but its position in pressure-temperature space is not known. It is possible that further work on the feldspars may permit the estimation of temperatures of formation from the compositions of the coexisting feldspars. When data on either of these systems is available, it will be possible to evaluate more critically the uncertainties found in this study. At present the temperature and pressure of metamorphism cannot be satisfactorily estimated.

ORIGIN OF THE NAIRNE PYRITIC FORMATION

The Nairne Pyritic Formation is believed to be an original sulfide-bearing sediment. The main points leading to this decision have all been discussed in detail, but, are summarized below:

1. The wide extent of the Nairne Pyritic Formation and the constancy of composition along its length.
2. The complete conformity of the sulfide-bearing rocks with all sedimentary features, including minor cross-bedding and lensing of sediments.
3. The close relationship between grain size of the silicate minerals and grain size of the sulfides, especially in graded beds.
4 The strict conformity between variations in sulfide content and composition, with the bedding.
5. Existence of planes of tiny pyrrhotite crystals parallel to the bedding, within massive pyrite layers, showing variations in the initial sedimentary sulfide composition.
6. Compatible relations between pyrite and pyrrhotite and between the sulfides and silicate minerals, indicating they were all involved in the metamorphism.

There is no apparent relation between the distribution of the sulfides and the structure of the Kanmantoo Group. Were the sulfides deposited from hydrothermal solutions or concentrated by lateral secretion one would certainly expect the deposition to be structurally controlled. Even if a favorable bed replacement is proposed one would expect that structure would have a definite effect on the distribution.

Edwards and Carlos (5) included the Nairne Pyritic Formation in their study on the selenium contents of some Australian sulfide deposits. On the basis of the S:Se ratio, which varied from 1:9,950 to 1:37,400 for the five samples analyzed, they concluded that the sulfides were of hydrothermal origin. It is felt that Edwards and Carlos' argument is weakened by having only five samples and by the limited background knowledge on the S:Se ratio of sulfides from deposits of different ages and known origin.

The method of deposition of the sediments is open to speculation. The concentration of pyrite in bands in the coarser rocks and at the base of graded beds, suggests heavy mineral separation. However, the complete absence of concentration of either pyrite or pyrrhotite in many beds is confusing. It is possible that in the finer grains the grain size effect predominated over specific gravity differences. There is no evidence that the sediments were sufficiently fine-grained for this to occur however, and a more probable explanation is that the original sulfide or sulfides had an altogether different composition from those observed today.

To explain the lack of pronounced heavy mineral separation the original sulfides must have had a lower specific gravity than pyrite or pyrrhotite. Hydrous iron sulfides would be the most likely compounds filling all the requirements. There is some basis to this suggestion in that hydrotroilite ($FeS.nH_2O$) and other hydrous iron sulfides of indefinite composition, such

as melnikovite are known to exist both naturally and experimentally (12). Where the natural hydrous iron sulfides have been observed in modern sediments they are associated with carbonaceous material. No carbonaceous material has been observed in the Nairne Pyritic Formation and the sediments could not have been original black muds.

Since some heavy mineral concentration has apparently occurred the original iron sulfides must have had a slightly higher specific gravity than the silicate minerals. Also, heavy mineral concentration and graded bedding mean the original iron sulfides must have been deposited as detrital grains and not chemically precipitated in situ. The possibility develops that the original iron sulfides were first chemically precipitated in shallow water and later redeposited in deep waters in the sediments as seen today. Later metamorphism has broken down the original sulfides to give the mineral assemblages observed today. Obviously the ratio of Fe to S must have varied in the original sediments since the ratio of pyrite to pyrrhotite varies widely from bed to bed.

The presence of graded bedding suggests deposition by turbidity currents. If the criteria for turbidity currents, as outlined by Rich (13), by Kuenen (10) and others, can be accepted, then one must propose the pyritic horizons being deposited in this way. In the redeposition any light carbonaceous material in the original muds may well have been dispersed. It is most unlikely that such a volume of sulfide minerals could be collected as primary detrital grains. If an exposed source area provided sediments so rich in detrital sulfides, surely other beds derived from the same source area must contain some evidence of sulfides. Since no other sulfide-bearing beds have been found, it is considered unlikely that primary detrital concentration of iron sulfides is of importance in this case. Further, primary detrital grains of pyrite and pyrrhotite would show pronounced heavy mineral concentration.

The method of formation suggested is one of chemical precipitation of hydrous iron sulfide in a shallow water environment followed by redeposition in deep water sediments.

ACKNOWLEDGMENTS

Many people have assisted directly and indirectly with this study. Dr. Keith Norrish and John Hutton of the C.S.I.R.O. have been helpful and informative with analyses and discussions. The regional field work was done in company with Dr. A. W. Kleeman and many ideas have come from him. My wife has, as usual, been a patient confidant and critic. Robin Offler assisted in much of the field work and has always been a willing helper. Miss A. M. C. Swan drafted the figures. Finally, Mr. J. Hammer of Nairne Pyrites Ltd. has always been willing and cooperative with visits to the Shephard Hill quarry.

UNIVERSITY OF ADELAIDE,
SOUTH AUSTRALIA,
Nov. 25, 1957

REFERENCES

1. Arnold, R. G., 1956a, The pyrrhotite-pyrite relationship: Carnegie Inst. Washington Year Book 55, for 1955–56, p. 177–178.
2. ——, 1956b, Subsolidus relations in the system FeS-FeS_2 (Abstr.): Geol. Soc. Am. Bull., v. 67, p. 1667.
3. ——, 1957, Report in Carnegie Inst. Washington Year Book No. 56, for 1956–57, p. 194.
4. Edwards, A. B., 1949, Pyritic deposit at Nairne, South Australia: Mining Review 90, South Australian Dept. Mines, p. 89–91.
5. ——, and Carlos, G. C., 1954, The selenium content of some Australian sulphide deposits: Australian Inst. Min. Metallurgy Proc. 172, p. 31–63.
6. Eugster, H. P., and Yoder, H. S., 1954, The stability and occurrence of paragonite (Abstr): Geol. Soc. America Bull., v. 65, p. 1248.
7. ——, and ——, 1955, The system potassium feldspar-albite-corundum-water: Carnegie Inst. Washington Year Book 54, p. 126–127.
8. Kleeman, A. W., and White, A. J. R., 1956, The structural petrology of portion of the Eastern Mt. Lofty Ranges: Jour. Geol. Soc. Australia, v. 3, p. 17–31.
9. ——, and Skinner, B. J., 1958, The Kanmantoo Group in the Strathalbyn-Harrogate region, South Australia: (in press).
10. Kuenen, P. H., 1957, Sole markings of graded graywacke beds: Jour. Geology, v. 65, p. 231–258.
11. Kullerud, G., 1953, The FeS-ZnS system, a geological thermometer: Nork. geol. Tidsskr., v. 32, p. 61–147.
12. Lepp, H., 1957, The synthesis and probable geologic significance of melnikovite: Econ. Geol., v. 52, p. 528–535.
13. Rich, J. L., 1951, Three critical environments of deposition and criteria for recognition of rocks deposited in each of them: Geol. Soc. America Bull., v. 62, p. 1–20.
14. Sprigg, R. C., Whittle, A. W. G., and Campana, B., 1951, Adelaide Military Sheet: Geol. Atlas of S. Australia.
15. ——, and Campana, B., 1953, The age and facies of the Kanmantoo Group: Aust. Jour. Sci., v. 16, p. 12–14.
16. ——, and Wilson, R. B., 1954, Echunga Military Sheet: Geol. Atlas of S. Australia.
17. Thompson, J. B., 1955, The thermodynamic basis for the mineral facies concept: Am. Jour. Sci., v. 253, p. 65–103.
18. Yoder, H. S., and Eugster, H. P., 1955, Synthetic and natural muscovites: Geochim. et Cosmochim. Acta. v. 8, p. 225–280.
19. ——, Stewart, D. B., and Smith, J. R., 1957, Ternary feldspars: Carnegie Inst. Washington Year Book 56, for 1956–1957, p. 206–214.

Economic Geology
Vol. 53, 1958, pp. 563–576

RANK OF COAL AND METAMORPHIC GRADE OF ROCKS OF THE NARRAGANSETT BASIN OF RHODE ISLAND[1]

ALONZO W. QUINN AND HERBERT D. GLASS

CONTENTS

	PAGE
Abstract	563
Introduction	563
Acknowledgments	565
Narragansett basin	565
Coal	565
Metamorphic grade of the rocks	567
Rank of the coal	569
Chemical analysis	569
X-ray analysis	571
Conclusions	575
References	575

ABSTRACT

The coal and the associated sedimentary rocks of the Narragansett basin are progressively metamorphosed from north to south and southwest. X-ray analysis seems to give more definite indication of rank of these high-ash high-rank coals than does chemical analysis.

Both chemical analysis and X-ray analysis reveal a close correspondence between rank of coal and metamorphic grade of associated rocks. At Pawtucket, coal, judged on the basis of X-ray analysis to be anthracite, is associated with rocks of the muscovite-chlorite subfacies of the greenschist facies that contain muscovite, paragonite, and chlorite. At Portsmouth, meta-anthracite is associated with rocks still in the muscovite-chlorite subfacies and containing muscovite, chlorite, and ilmenite. At the Cranston mine, higher-rank meta-anthracite is associated with rocks in the biotite-chlorite subfacies.

INTRODUCTION

THE purpose of the present paper is to establish a connection between rank of coal and metamorphic grade of rocks. Many geologists have traced the variations in rank of coals and many other geologists have made intensive studies of the variation in grade of metamorphosed sedimentary rocks. A massive literature has been created in each of these fields, but there is very little contact between them. This lack of contact is due in part to the fact that most coals of anthracite and lower rank are associated with sedimentary rocks that are not metamorphosed. Furthermore, most of those metamorphic rocks that

[1] Publication authorized by the Director, U. S. Geological Survey, and by the Chief, Illinois State Geological Survey.

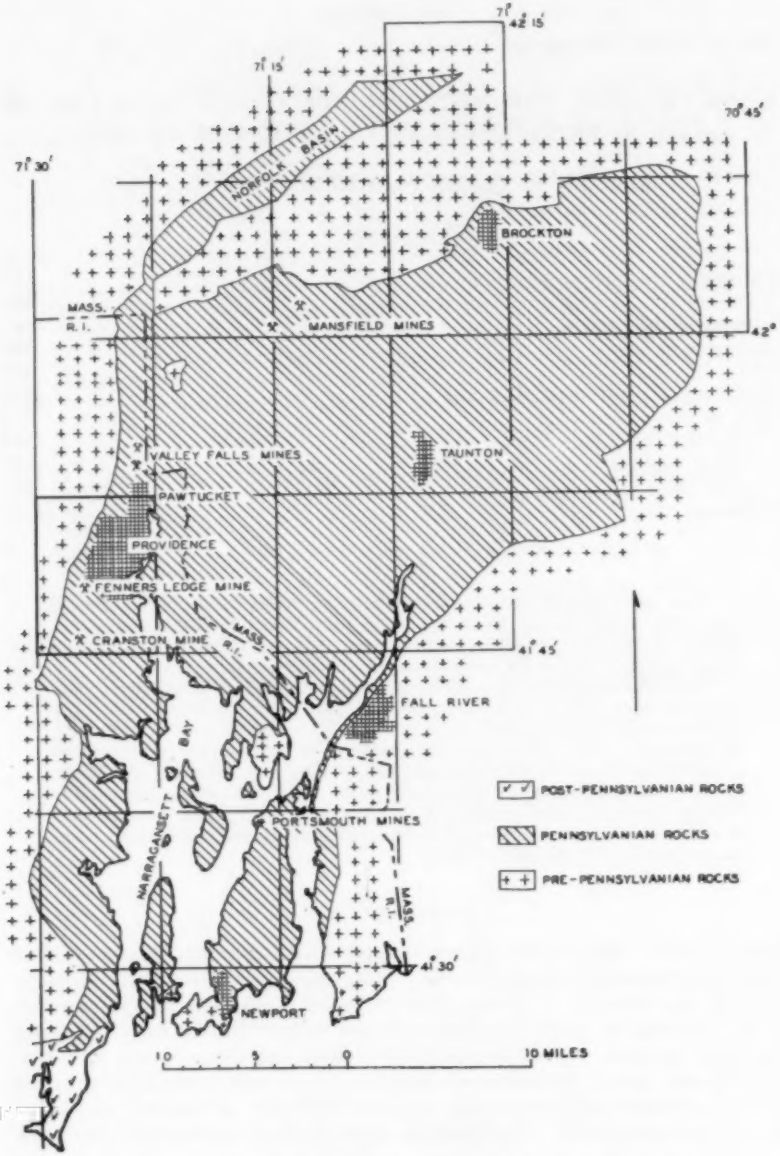


FIG. 1. Sketch map of Narragansett basin; heavy line around Providence quadrangle.

have been studied carefully do not contain coals that have been analyzed by the methods of coal analysis.

However, the Narragansett basin of Rhode Island contains progressively metamorphosed sedimentary rocks interbedded with coaly layers that have been mined as fuel and, consequently, studied by coal analysis. This provides an opportunity to make a comparison of the rank of coal with the metamorphic grade of closely associated sedimentary rocks.

Acknowledgments.—This paper describes incidental results from a cooperative project of the Rhode Island Development Council and the United States Geological Survey. The X-ray diffraction work was done at the laboratories of the Illinois State Geological Survey. Three analyses of coal from the Pawtucket tunnel were made by the United States Bureau of Mines for use in this study, and an additional analysis was made by Walter M. Saunders, chemist, of Providence, Rhode Island. Mr. Roy F. Abernethy and Mr. B. C. Parks of the U. S. Bureau of Mines kindly gave advice on the use of these analyses, but they do not necessarily agree with the conclusions of this paper. The authors appreciate both the analyses and the advice.

NARRAGANSETT BASIN

The Narragansett basin is a complex synclinal mass of sedimentary rocks of Pennsylvanian age (Fig. 1). The rocks of the basin are extremely varied and include chiefly sandstone, shale, conglomerate, arkose, graywacke, and meta-anthracite. Most of the rocks are gray or black, but the Wamsutta formation in the northwest is mostly red. Feldspars and lithic fragments are common throughout. Cross-bedding and lensing of the beds are characteristic. All these rocks seem to be of continental origin.

Fossil plants, which have been found at many places within the basin, are the basis for assignment to the Pennsylvanian system. Study of the plant fossils is, for the most part, of a rather early date (10, 11, 12, 15, 16, 17), but Knox (8) in 1944 assigned an early or middle Allegheny age to the Wamsutta formation.

The rocks of the Narragansett basin were folded, faulted, and variably metamorphosed during the Appalachian revolution in Pennsylvanian time (13).

The coals discussed in this report were taken from three localities, a tunnel near the north border of the Providence quadrangle, the Cranston mine near the south border of the Providence quadrangle, and the Portsmouth mines (Fig. 1). The rocks here discussed came from the same places and also from several places in the Providence quadrangle between the tunnel and the Cranston mine (Fig. 2).

COAL

The coal of the Narragansett basin has long attracted attention, both because of possible commercial use and because of scientific interest in its high rank. Ashley (2, p. 5) wrote, "Its situation, directly on the seaboard and in the center of a region of dense population and large manufactures, gives it

a great advantage in the New England markets over other coals through reduced cost of transportation, an item that adds largely to the cost of the coals with which New England is now supplied. Lured by this apparent advantage, company after company has sought to exploit the coal or to utilize it in metallurgic enterprises in which they were interested; but the fact remains

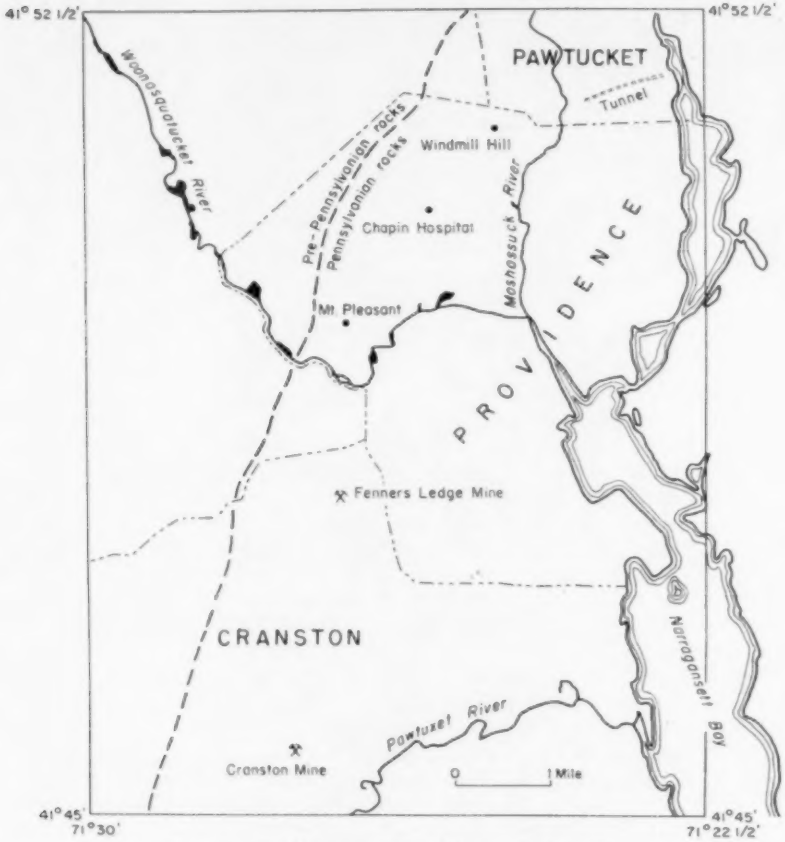


FIG. 2. Sketch map of Providence quadrangle.

that Rhode Island anthracite is still unused commercially and the impression has become general that, considered as a source of heat, it is more of a will-o'-the-wisp than a reality."

Ashley cited the Taunton Copper Company's operation of the Portsmouth mine as "the one shining example of continued successful use of Rhode Island coal" (p. 10). This reported use (1860–1883), for smelting copper ore from

Cuba and South America, seems almost incredible, but a considerable mass of copper slag remains on the shore near the abandoned mine.

The Cranston mine may now be cited as a second "shining example," for the present operators, Graphite Mines, Inc., have been mining continuously since 1940. Continuous, or almost continuous, operation by previous companies is reported to have begun in 1914. The product has been used as fuel and now is used chiefly as foundry graphite.

The coal beds are widely distributed throughout the Narragansett basin. Apparently most of them are thin and discontinuous, but the bed at the Cranston mine is more than 20 feet thick (19). None of them has been traced more than a few thousand feet. Most of the coal is shiny black and is transected by curved slickensides, but some specimens from Portsmouth have the blocky fracture characteristic of many coals of lower rank. Veinlets of quartz, calcite, pyrite, and aphrosiderite (partly replaced by fibrous quartz) are common in and near the coal beds.

METAMORPHIC GRADE OF THE ROCKS

Thin section studies of the rocks were supplemented by X-ray diffraction studies. All the rocks studied contain considerable fine-grained material that could not be identified microscopically. Figure 3 illustrates the type of X-ray curve given by the rocks.

It has long been known that the sedimentary rocks of the Narragansett basin are more metamorphosed in the south and southwest than in the north and northeast (9, 17). The rocks north of Pawtucket are essentially unmetamorphosed, although strongly indurated. Rocks near the mouth of Narragansett Bay are metamorphosed to mica schist and garnet-staurolite schist. So little is known of structural details that it is not feasible to plot isograds or metamorphic facies in the basin as a whole. Within the Providence quadrangle, which includes the Pawtucket tunnel and the Cranston mine, there are several metamorphic changes from north to south, although here, too, structural details are not well enough known to permit drawing isograds. The metamorphism here is of the type generally included in regional metamorphism.

The rocks intersected by the Pawtucket tunnel have been affected by only the beginning of metamorphism. The quartz sand grains are sharp, angular, and randomly oriented, much as when originally deposited. Minerals identified in thin section are quartz, white mica, chlorite, microperthite, albite, calcite in veinlets and rhombohedral grains, and accessory tourmaline, epidote, hematite, and leucoxene. The only minerals of probable metamorphic origin are fine-grained white mica and chlorite in the matrix. Examination by X-ray diffraction reveals that some of the white mica is paragonite and some is muscovite, but these were not distinguished by optical properties.

At Windmill Hill (Fig. 2) the quartz sand grains are somewhat broken and strained but have approximately their original shapes. The edges of the grains are interfingered with white mica. Minerals identified in thin section are quartz, white mica, chlorite, ilmenite, and accessory zircon and

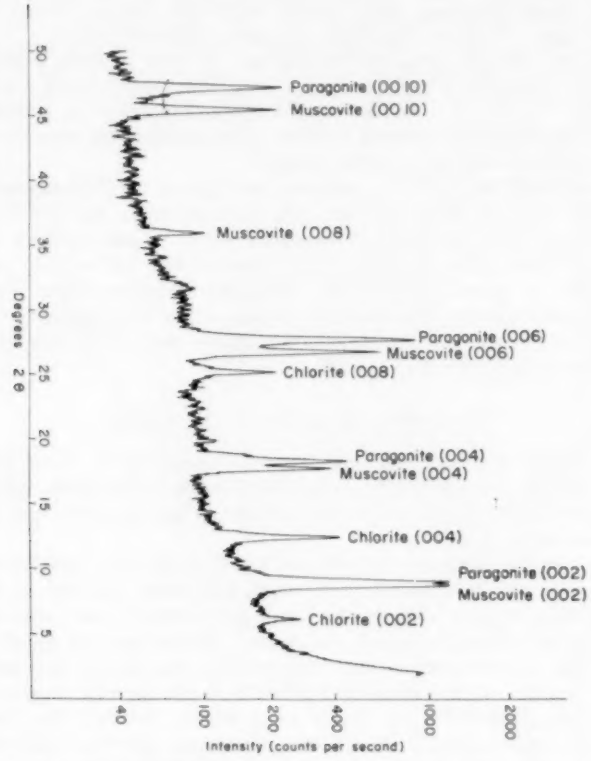


FIG. 3. X-ray spectrometer tracing of oriented aggregate ($< 22\mu$) from rocks at Mount Pleasant showing the sequence of (001) reflections for muscovite, paragonite, and chlorite.

tourmaline. The white mica and the chlorite occur in larger flakes of undoubted metamorphic origin, and ilmenite is present as a new metamorphic mineral.

At Mount Pleasant the quartz grains are lens-shaped and interlocked with other grains. Minerals identified in thin section are white mica, chloritoid in radial aggregates, quartz, ilmenite, chlorite, and accessory tourmaline. Increasing regional metamorphism accounts for the presence of chloritoid. Some of the white mica is paragonite, as is shown in Figure 3.

At the Fenners Ledge mine the quartz grains are lens-shaped and interlocked. Minerals identified in thin section are quartz, white mica, ilmenite, chloritoid, and accessory tourmaline. Some of the white mica is paragonite and the chloritoid is in large separate crystals.

At the Cranston mine the quartz grains are lens-shaped and interlocked.

Minerals identified in thin section are quartz, white mica, biotite, ilmenite, chlorite, albite, and accessory zircon and tourmaline. Of special interest is the appearance of biotite here. Chloritoid was not seen. Paragonite was not detected at the Cranston mine or to the southwest, although samples of different lithologic types were tested. The absence of paragonite suggests that it is eliminated here at an unusually low metamorphic rank (14). Garnet is present in the rocks about a mile and a half to the southwest, but was not seen at the Cranston mine.

The rocks at Portsmouth are somewhat less metamorphosed than are those at Cranston but more metamorphosed than those at Pawtucket. The quartz grains at Portsmouth are considerably elongated and interlocked. Minerals identified in thin section are quartz, white mica, chlorite, ilmenite, and albite, and accessory microperthite, calcite, tourmaline, apatite, and pyrite. Biotite was not seen and paragonite was not detected by X-ray study.

Progressive metamorphism is thus indicated both by the minerals developed and by the physical deformation of the original grains. All these rocks are in the greenschist facies. At the Pawtucket tunnel they are in the muscovite-chlorite subfacies and at the Cranston mine they are in the biotite-chlorite subfacies.

RANK OF THE COAL

Chemical Analysis.—Table 1 contains all usable analyses of coals from the Cranston mine, the Portsmouth mines, and a tunnel bored in Pawtucket in 1954–55. Several other mines were opened at one time or another (Fig. 1), but available analyses from these are too few for making even tentative studies. Most of the analyses of Narragansett basin coals could not be used because they were made many years ago when different methods were used and different standards of accuracy were maintained. The analyses of Jackson (7) in 1840 and Emmons (4) in 1885 seem too uncertain for safe use. Those presented in 1915 by Ashley (2) are used, however. Several from the Cranston mine are of fairly recent date (19), and most recent are four from coals intersected by the tunnel in Pawtucket. A further difficulty in using the available analyses arises from the fact that most Narragansett basin coals have a high content of ash that hinders accurate analytical determination of both volatile matter and ash (Roy F. Abernethy, Analysis Section, U. S. Bur. Mines, written communication).

All these coals are meta-anthracite, according to the classification of the American Society for Testing Materials (1, 5). However, the calculation, by Parr's formula, gives values of more than 100 percent fixed carbon for several of these Rhode Island coals, probably because of the adverse effect of the high content of ash.

On the basis of grade of rock metamorphism, it might be expected that the lowest rank of coal would be at the Pawtucket tunnel, an intermediate rank at Portsmouth, and the highest rank at Cranston. The coal analyses of Table 1 are in agreement with this. The averages of ultimate carbon, moisture-free and ash-free, are 92.3 percent at the Pawtucket tunnel (3 analyses),

93.7 percent at Portsmouth (8 analyses), and 95.4 percent at Cranston (4 analyses). The averages of fuel ratios (FC/VM) are 15.9 at Pawtucket (4 analyses), 21.7 at Portsmouth (9 analyses), and 23.8 at Cranston (11 analyses). The averages of dry, mineral-matter-free fixed carbon are 98.75 at Pawtucket (4 analyses), 99.1 at Portsmouth (8 analyses), and 99.2 at Cranston (11 analyses).

Although these averages correspond with the differences of rock metamorphism, the number of analyses is small, the amount of variation between different analyses from the same locality is large, and there is considerable overlap of analyses from the different localities. Additional analyses might yield more significant averages, but it does not seem probable that more analyses of the Narragansett basin coals will be forthcoming, except possibly from the operating Cranston mine. At best, conventional chemical analyses do not yield entirely reliable indications of rank of high-ash anthracite and

TABLE 1 (a)

RHODE ISLAND COALS. ANALYSES—AS RECEIVED

	No.	Proximate				Ultimate					BTU
		Moist.	VM	FC	Ash	S	H	C	N	O	
Pawtucket	E-72739	9.0	4.2	49.7	37.1	2.0	1.7	49.3	.2	9.7	7410
	E-72740	7.8	3.0	52.6	36.6	.5	1.5	52.2	.2	9.0	7720
	E-69728	9.6	3.9	61.8	24.7	1.9	1.9	60.2	.3	11.0	9110
	173554 (100.3)	2.4	3.7	68.6	25.6	1.3					
Portsmouth	C-44412	8.6	2.2	71.9	17.3	.0	1.0	73.2	.1	8.4	
	9328	16.8	2.3	64.4	16.5	.6	2.1	62.6	.3	17.9	9230
	9329	13.3	2.5	65.3	18.9	.3	1.9	64.2	.2	14.5	9313
	9330	23.7	3.0	42.5	30.8	.0	3.1	42.4	.1	23.6	5976
	9331	22.9	2.8	58.4	15.9	.1	2.8	58.5	.2	22.5	8528
	9335	15.9	2.5	49.8	31.8	.1	2.4	47.9	.2	17.6	7300
	9336	16.6	3.5	46.0	33.9	.2	2.1	45.5	.1	18.2	6545
	9337	14.1	4.0	61.9	20.0	.1	1.9	62.5	.1	15.4	8895
	9338	13.9	2.5	63.2	20.4	1.3	1.8	62.1	.2	14.2	9040
Cranston	C-37658	.2	3.0	64.1	32.7	.3	.4	64.2	.1	2.3	8720
	7769	9.7	2.6	62.0	25.7	.1					8822
	7770	4.5	3.5	59.7	32.2	.1					8411
	7771	4.5	3.0	78.7	13.8	.8	.9	78.7	.1	5.7	11097
	7772	7.3	1.7	73.1	17.9	.1					10364
	113	2.4	4.9	73.6	19.1	.1	.9	75.1	.1	4.7	10996
	190	3.7	2.1	71.5	22.7						
	191	4.8	2.5	69.9	22.8	.1					
	194	11.5	3.4	63.6	21.5	.6					
	FS-74	.1	3.8	62.1	34.0	.5	.4	62.8	.1	2.2	8800
	FS-75 (99.8)	.2	3.1	56.4	40.1	.5	.3	56.5	.1	2.5	7910

E-72739, E-72740, E-69728 analyses by Bureau of Mines, 1955.
173554 analysis by Walter M. Saunders, Providence, 1955.
C-37658, C-44412 analyses by Bureau of Mines, Rept. Investig. 4276, p. 37.
7769, 7770, 7771, 7772, 113, 190, 191, 194, Ashley, U. S. Geol. Survey, Bull. 615, p. 27.
9328, 9329, 9330, 9331, 9335, 9336, 9337, 9338 Ashley, U. S. Geol. Survey, Bull. 615, p. 26.
FS-74, FS-75 Crawford and others, Univ. R. I., Engin. Exper. Sta., Bull. 3, p. 23.
Figures of quoted analyses have been rounded off to tenths of a percent and a few errors have been corrected.

TABLE 1 (b)

RHODE ISLAND COALS. ANALYSES—MOISTURE-FREE AND ASH-FREE

	No.	Proximate		Ultimate					BTU
		VM	FC	S	H	C	N	O	
Pawtucket	E-72739	7.8	92.2	3.8	1.4	91.5	.4	2.9	13750
	E-72740	5.4	94.6	.9	1.1	93.9	.4	3.7	13890
	E-69728	6.0	94.0	2.8	1.3	91.6	.5	3.8	13870
	173554	5.1	94.9						
						92.3 avg.			
Portsmouth	C-44412	3.0	97.0						
	9328	3.4	96.6	.9	.4	93.8	.4	4.5	13831
	9329	3.7	96.3	.4	.6	94.7	.3	4.0	13723
	9330	6.6	93.4	.1	1.1	93.0	.2	5.6	13120
	9331	4.5	95.5	.2	.5	95.6	.3	3.4	13946
	9335	4.8	95.2	.2	1.2	91.4	.3	6.9	13930
	9336	7.1	92.9	.3	.5	91.9	.2	7.1	13200
	9337	6.1	93.9	.1	.6	94.8	.1	4.4	13490
	9338	3.8	96.2	2.1	.4	94.5	.3	2.7	13770
						93.7 avg.			
Cranston	C-37658	4.5	95.4	.4	.4	95.8	.1	3.3	
	7769	3.9	96.1	.1					13658
	7770	5.5	94.5	.2					13325
	7771	3.7	96.3	1.0	.5	96.3	.1	2.1	13583
	7772	2.3	97.7	.9	.4	93.8	.4	4.5	13858
	113	6.2	93.8	.1	.8	95.6	.2	3.3	14002
	190	2.9	97.1	.1					
	191	3.5	96.5	.1					
	194	5.1	94.9	.8					
	FS-74	5.8	94.2	.1					
	FS-75	5.2	94.8	.8					
						95.4 avg.			

meta-anthracite. Therefore, X-ray diffraction studies were made for the purpose of testing and supplementing the chemical analyses.

X-ray Analysis.—X-ray diffraction has been demonstrated to be of value in the study of coal structure (18). It is particularly useful in determining the relative degree of graphitization for highest rank coals that show different stages in coalification. The degree of graphitization may be estimated by the shape and position of the graphite X-ray diffraction lines (6).

Figure 4 shows smoothed X-ray spectrometer tracings (Cu radiation) for three reference materials of different degrees of graphitization. Curve A is for a relatively pure commercial graphitic carbon. The structure of such material is not as ordered as that of crystalline graphite although a complete sequence of graphite reflections may be observed.

Curve B represents the meta-anthracite near Leoben, Austria—FC 98.2 percent (unit coal), ash 7.2 percent (as received). The presence of almost all graphite reflections indicates a high degree of graphitization in the coal. However, some decrease in intensity and increase in broadening of all peaks

TABLE 1 (c)

RHODE ISLAND COALS. FUEL RATIOS AND AVERAGES

	No.	As received		FC/VM	Moisture-free ash-free		Ultimate C	Dry, mineral-matter-free fixed carbon
		VM	FC		VM	FC		
Pawtucket	E-72739	4.2	49.7	11.8	7.8	92.2	91.5	99.0
	E-72740	3.0	52.6	17.5	5.4	94.6	93.9	99.8
	E-69728	3.9	61.8	15.8	6.0	94.0	91.6	97.8
	173554	3.7	68.6	18.5	5.1	94.9		98.4
				15.9	6.1	93.9	92.3	98.75 avg.
Portsmouth	C-44412	2.2	71.9	32.7	3.0	97.0	99.3	
	9328	2.3	64.4	28.0	3.4	96.6	93.8	98.3
	9329	2.6	65.3	26.1	3.7	96.3	94.7	99.1
	9330	3.0	42.5	14.2	6.6	93.4	93.0	100.2
	9331	2.8	58.4	20.9	4.5	95.5	95.6	98.0
	9335	2.5	49.8	19.9	4.8	95.2	91.4	101.4
	9336	3.5	46.0	13.1	7.1	92.9	91.9	99.8
	9337	4.0	61.9	15.5	6.1	93.9	94.8	96.9
	9338	2.5	63.2	25.3	3.8	96.2	94.5	99.2
				21.7	4.8	95.2	93.7	99.1 avg.
Cranston	C-37658	3.0	64.1	21.4	4.5	95.5	95.8	100.5
	7769	2.6	62.0	23.8	3.9	96.1		100.0
	7770	3.5	59.7	17.1	5.5	94.5		99.3
	7771	3.0	78.7	26.2	3.7	96.3	96.3	96.8
	7772	1.7	73.1	43.0	2.3	97.7	93.8	100.1
	113	4.9	73.6	15.0	6.2	93.8	95.6	96.1
	190	2.1	71.5	34.0	2.9	97.1		100.3
	191	2.5	69.9	27.9	3.5	96.5		99.7
	194	3.4	63.6	18.7	5.1	94.9		98.0
	FS-74	3.8	62.1	16.3	5.8	94.2		99.4
	FS-75	3.1	56.4	18.2	5.2	94.8		101.3
				23.8	4.4	95.5	95.4	99.2 avg.

$$\text{moist FC} \times \frac{100}{100 - (\text{moisture} + 1.1\ \text{ash})} = \text{dry, mineral-matter-free fixed carbon (Fieldner and others, 1939, p. 5)}$$

indicates a lower degree of graphitization than that of the graphitic carbon.

Curve C represents an anthracite from Pennsylvania—FC 97.7 percent (unit coal), ash 8.4 percent (as received). It readily can be observed from the X-ray tracings that a major difference exists between the anthracite and meta-anthracite structures although the difference in amount of fixed carbon is only 0.5 percent. The diffraction peaks for anthracite are relatively few and extremely broad. Evidently a discontinuity in rank exists between anthracite and meta-anthracite.

Figure 5 shows the X-ray spectrometer tracings for the three Narragansett basin coals. The curves show only graphite reflections and all peaks caused by impurities have been removed. Curve A shows the meta-anthracite from Cranston. All graphite reflections are present and the degree of graphitiza-

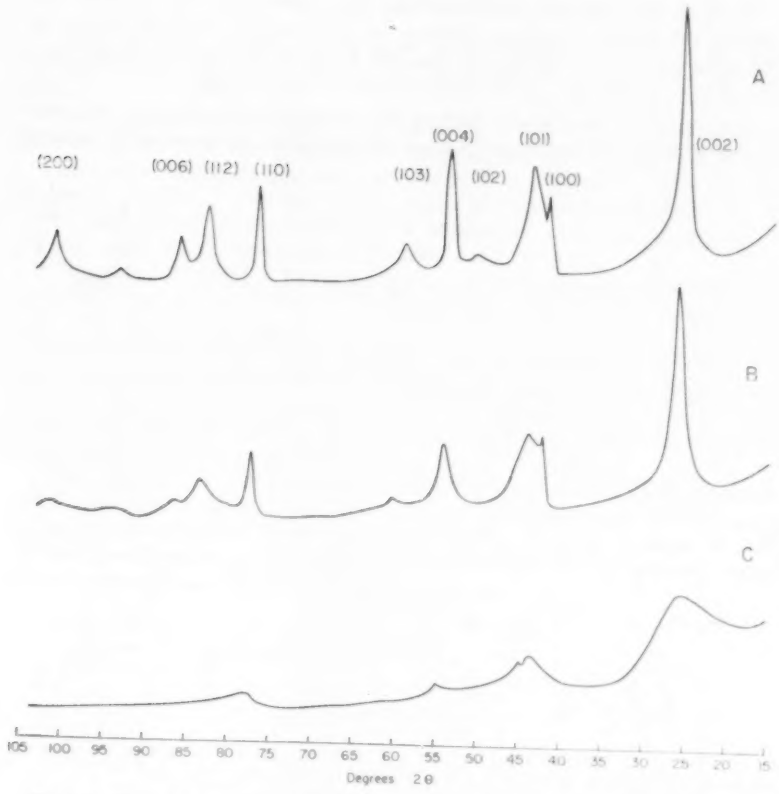


FIG. 4. X-ray spectrometer tracings of reference graphitic materials. A. Commercial graphitic carbon. B. Meta-anthracite, near Leoben, Austria. C. Anthracite, Pennsylvania.

tion is almost identical with that of the Leoben meta-anthracite (Fig. 4, curve B). Curve B, for the Portsmouth meta-anthracite, shows elimination of the (103) and (200) peaks and noticeable broadening of all others. The coal still retains the meta-anthracite structure but is less graphitized than the Cranston coal. Curve C, for the Pawtucket coal, contains only the reflections found in anthracite and therefore is not considered meta-anthracite in rank.

It is apparent that the highest rank of meta-anthracite is found at Cranston, and the Portsmouth coal is somewhat lower in rank although still considered meta-anthracite. The Pawtucket coal is of lowest rank and the X-ray diffraction curve is definitely of the type generally given by anthracite.

Thus, X-ray evidence indicates that the Pawtucket coal is anthracite, although the chemical analyses indicate meta-anthracite. In view of the uncertainties involved in the use of chemical analyses of high-rank coals, especially of those with high ash, X-ray study seems more reliable.

It is apparent also that the rank of the coal is directly related to the metamorphic grade of the rocks, and a close correlation exists between the mineral

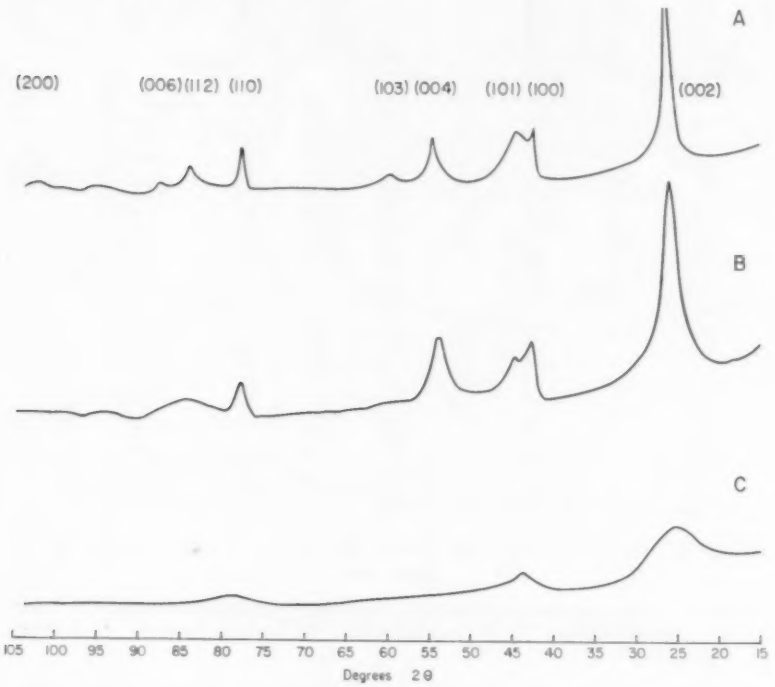


FIG. 5. X-ray spectrometer tracings of Narragansett basin coals. A. Cranston. B. Portsmouth. C. Pawtucket.

assemblages of the rocks and the rank of the coal. The presence of paragonite in these rocks may well be associated only with the rank of anthracite, whereas its absence may indicate a higher metamorphic grade associated with meta-anthracite development. In terms of metamorphic grade, the muscovite-chlorite greenschist subfacies is associated with anthracite and with the lowest rank meta-anthracite; the biotite-chlorite subfacies is associated with meta-anthracite of higher rank.

CONCLUSIONS

X-ray analysis seems to give a more definite measure of rank of the Narragansett basin high-ash anthracite and meta-anthracite than does chemical analysis.

Both chemical analysis and X-ray analysis reveal a close correspondence between rank of coal and metamorphic grade of associated rocks.

The anthracite of Pawtucket is associated with sandstone, shale, and conglomerate that show only the lowest marks of rock metamorphism: the development of chlorite, paragonite, and muscovite. This is the muscovite-chlorite subfacies of the greenschist facies.

The meta-anthracite at Portsmouth is associated with rocks that have been metamorphosed to the ilmenite-muscovite-chlorite stage. This is still in the muscovite-chlorite subfacies.

The meta-anthracite of the Cranston mine is associated with rocks that have been metamorphosed beyond the chloritoid stage into the biotite stage, but apparently not to the garnet stage. This degree of rock metamorphism has not been enough to change the coal completely to graphite, nor to remove it hopelessly from the category of fuel.

Thus, the rank of coal increases, through the lower ranks of subbituminous and bituminous, to the anthracite stage before conditions become severe enough to cause metamorphism of the associated rocks. Further increase of rank within the anthracite stage and into the meta-anthracite and graphite stages occurs under the conditions of rock metamorphism.

BROWN UNIVERSITY AND U. S. GEOLOGICAL SURVEY,
ILLINOIS STATE GEOLOGICAL SURVEY,
Dec. 7, 1957

REFERENCES

1. American Society for Testing Materials, 1939 Standard specifications for classification of coals by rank (A.S.T.M. Designation: D388-38): 1939 Book of A.S.T.M. Standards, pt. 3, 1–6.
2. Ashley, G. H., 1915, Rhode Island coal: U. S. Geol. Survey Bull. 615.
3. Crawford, T. S., Corey, R. C., Schwartz, C. H., Spano, L. A., and Carpenter, E. L., 1953, A slagging gas producer for the production of mineral wool from Rhode Island meta-anthracite: Univ. of Rhode Island Eng. Exp. Sta. Bull. 3.
4. Emmons, A. B., 1885, Notes on the Rhode Island and Massachusetts coals: Am. Inst. Min. Eng. Trans., v. 13, p. 510–517.
5. Fieldner, A. C., Selvig, W. A., and Frederic, W. H., 1939, Classification chart of typical coals of the United States: U. S. Bur. Mines Rept. Inv. 3296R.
6. Franklin, R. E., 1951, The structure of graphitic carbons: Acta Crystallographica, v. 4, pt. 3, p. 253–261.
7. Jackson, C. T., 1840, Report on the geological and agricultural survey of the State of Rhode Island: 312 p., B. Cranston & Co., Providence.
8. Knox, A. S., 1944, A Carboniferous flora from the Wamsutta formation of southeastern Massachusetts: Am. Jour. Sci., v. 242, p. 130–138.
9. Lahee, F. H., 1912, Relations of the degree of metamorphism to geologic structure and to acid igneous intrusion in the Narragansett Basin, Rhode Island: Am. Jour. Sci., 4th ser., v. 33, p. 249–262, 354–372, 447–469.
10. Lesquereux, Leo, 1880–1884, Description of the coal flora of the Carboniferous formation in Pennsylvania and throughout the United States: Pennsylvania Geol. Survey, 2d, Rept. of Progress, P., v. 3.

11. Lesquereux, Leo, 1884, The Carboniferous flora of Rhode Island: Am. Naturalist, v. 18, p. 921–923.
12. Lesquereux, Leo, 1889, Fossil plants of the coal measures of Rhode Island: Am. Jour. Sci., 3rd ser., v. 37, p. 229–230.
13. Quinn, A. W., Jaffe, H. W., Smith, W. L., and Waring, C. L., 1957, Lead-alpha ages of Rhode Island granitic rocks compared to their geologic ages: Am. Jour. Sci., v. 255, p. 547–560.
14. Rosenfeld, J. L., 1956, Paragonite in the schist of Glebe Mountain, southern Vermont: Am. Mineralogist, v. 41, p. 144–147.
15. Round, E. M., 1924, Correlation of fossil floras of Rhode Island and New Brunswick: Bot. Gazette, v. 78, p. 116–118.
16. Round, E. M., 1927, Correlation of coal flora of Henry County, Missouri, and the Narragansett Basin: Bot. Gazette, v. 83, p. 61–69.
17. Shaler, N. S., Woodworth, J. B., and Foerste, A. F., 1899, Geology of Narragansett Basin: U. S. Geol. Survey Mon. 33.
18. Siever, Raymond, 1952, X-ray diffraction study of rank increase in coal: 2d Conf. on the Origin and Constitution of Coal, Crystal Cliffs, Nova Scotia, p. 341–360.
19. Toenges, A. L., Turnbull, L. A., Neale, Arthur, Schopf, J. M., Abernethy, R. F., and Quinn, A. W., 1948, Investigation of meta-anthracite in Newport and Providence counties, Rhode Island: U. S. Bur. Mines Rept. Inv. 4276, 37 p.

Economic Geology
Vol. 53, 1958, pp. 577–597

MANGANESE ORES FROM THE KURUMAN DISTRICT, CAPE PROVINCE, SOUTH AFRICA

J. J. FRANKEL

ABSTRACT

The newly explored manganese field north-west of Kuruman, Northern Cape Province, South Africa, is almost completely covered by younger rocks, such as Kalahari sand and calcrete. Borehole cores and quarry exposures show that the ore is a manganized limestone horizon interbedded with Upper Griquatown banded ironstones of the Transvaal System of presumed Precambrian age. The predominant minerals in the ores are braunite, cryptomelane and hausmannite. Veins of cross-fiber cryptomelane are an interesting mineralogical feature.

The limestone horizon, originally somewhat manganiferous, was the source of the manganese of the enriched ores. Manganization of the limestone is not significant at depth, but those parts of the horizon nearer surface and present sub-outcrop, have high manganese contents and show strong outcrop enrichment. It is considered that the ores are the result of near surface enrichment during several successive periods of erosion, and are not due to the introduction of the manganese by magmatic waters.

INTRODUCTION

MANGANESE ore specimens containing seams of a fibrous manganese mineral that simulates crocidolite asbestos in appearance, were given to me by Dr. L. G. Boardman in 1954. The ore came from the Smartt Mine of Messrs. South African Manganese, Limited, in the newly explored manganese field in the Kuruman district of the Northern Cape Province, Union of South Africa. The ore is so unlike that of the manganese deposits of Postmasburg in the south that a detailed study seemed desirable. A geological investigation of a part of this field was carried out by the author in July, 1956 and a suite of representative specimens was collected for further laboratory study.

Acknowledgments.—The cost of chemical analyses of fibrous cryptomelane was met by the Staff Research Fund of the University of Natal. Mr. K. E. Alexander of the Mount Edgecombe Sugar Experiment Station, Natal, kindly carried out some alkali determinations. Dr. T. L. Webb of the National Building Research Institute, Pretoria, made some differential thermal analyses. Dr. F. A. Raal of the Diamond Research Laboratory, Johannesburg, carried out X-ray diffraction identifications. Dr. J. N. van Niekerk and Mr. F. T. Wybenga of the X-ray Section of the National Physical Research Laboratory, Pretoria, have contributed a detailed X-ray analysis of the fibrous cryptomelane. Mr. P. J. Newman of the Department of Architecture, University of Natal, made the ore photomicrographs.

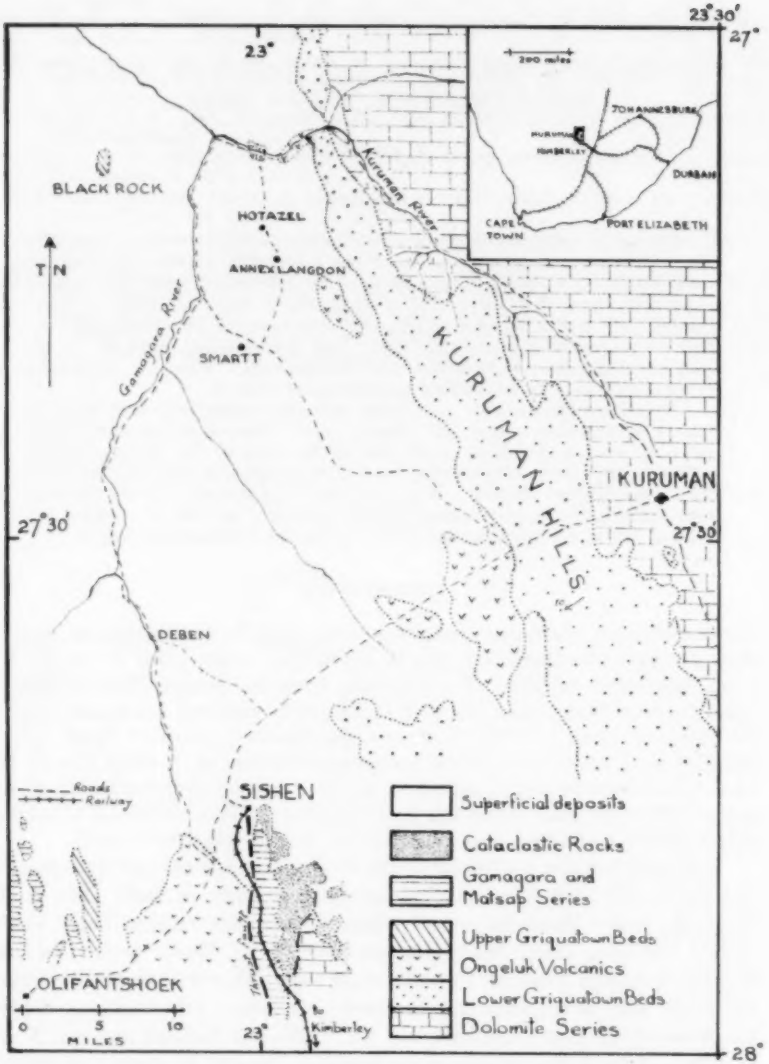


FIG. 1. Geological sketch map of the area west of Kuruman, Cape Province, compiled from Visser (11) and Union Geological survey maps.

I am indebted to Dr. L. G. Boardman for critical discussion in the field. Both he and Mr. P. R. Bosch supplied many specimens of the fibrous cryptomelane. I thank Messrs. South African Manganese, Limited, Johannesburg, for permission to visit their workings on the farms Smartt and Hotazel.

Messrs. National Manganese Mines, Limited, Johannesburg, have kindly allowed me to use data obtained at their mine on Annex Langdon, and Messrs. Philipp Brothers, Inc., New York, have provided a complete ore analysis and other assays.

It is with pleasure that I thank all who have helped in this investigation.

LOCALITY AND GENERAL GEOLOGY

The manganese ores with which this paper is concerned occur in an area approximately 50 miles north-west of the village of Kuruman in the Northern Cape Province, Union of South Africa (Fig. 1). The area forms part of the south-eastern verges of the Kalahari Desert. It is classed as Kalahari Thorn Country and has an average rainfall of 8 to 10 inches per annum. The rivers are dry for practically the whole year, with short-lived torrential flows particularly during wet years. Water is obtained from springs and boreholes. Temperatures often exceed 100° F in the shade in summer with very low humidity, while extremely cold nights are common in winter.

Except for an isolated hill of manganese and iron ore known as Black Rock in the north-west, the country west of the asbestos-bearing Kuruman hills is flat and lies at approximately 3,500 to 3,700 feet above sea level. Slight undulations on the peneplain are due to dunes or to the dry river valleys, such as that of the Gamagara River.

The nearest railhead is Sishen in the newly developed iron-ore deposits some 50 miles south of the southern end of this manganese field.

The area is covered by young superficial deposits varying from a few to as much as 300 feet in thickness, composed of clay beds, surface limestones, cemented ironstone rubble, ferricrete, and dunes of red Kalahari sand. The older rocks, especially those associated with the manganese ore, rarely crop out and the manganese ore itself, except for the Black Rock occurrence, was originally found only in wells and pits. The detailed geological structure is not clearly revealed by natural exposures. The extent and probable structure of the mineralized areas have been recently deduced from borehole information and magnetometric anomalies (4). The pre-Karroo geology is illustrated in Figures 2 and 3.

The manganized rocks lie in the upper part of the Griquatown series of the Transvaal System. The lower divisions of this system up to the Ongeluk lavas are well exposed along the eastern margin of the area, but pass under the superficial Kalahari sediments westwards. These exposures show that the older formation is regionally folded into broad anticlines and synclines.

The geological succession in the vicinity of the manganese mines is:

Kalahari sands (Lower Pleistocene?)		Mainly red wind-blown sands	
		(unconformity)	
Kalahari beds (Pre-lower Pleistocene?)		Clays, calcrete, ferricrete, etc.	
		(unconformity)	
Karroo system (Upper Carboniferous)	Dwyka series	Shales, tillite	
		(unconformity)	
Loskop system (Late Precambrian?)	Gamagara series	Mainly quartzites with basal conglomerate and aluminous shales	about 3,000 feet
		(unconformity)	
Transvaal system (Late Precambrian?)	Griquatown series (=Pretoria series)	3. Upper beds Ferruginous jaspers, dolomitic limestones, shales, manganese horizons	5,000 feet
		2. Andesitic (Ongeluk) lavas	3,000 feet
		1. Lower beds Minor tillite horizon, quartzites, shales, banded ironstones, some carrying crocidolite asbestos	2,000 feet
	Campbell Rand series (=Dolomite series)	Dolomitic limestones with limestone lenses	5,000 feet

FIELD SETTING OF THE MANGANESE ORE

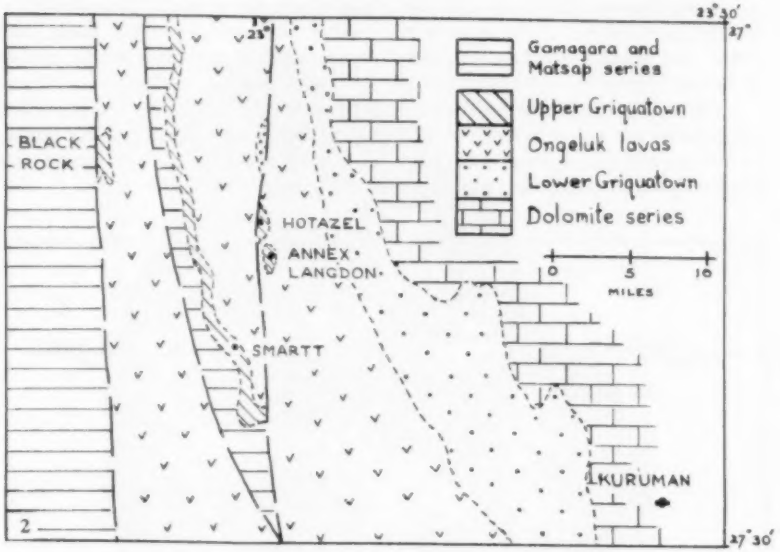
The structure of the ore bodies differs considerably from that of the Postmasburg manganese fields to the south. According to Kupferbürger and others (4), the thick massive manganese ore bodies are persistent over many miles of strike; the lowermost manganese horizon overlies about 100 feet of banded ironstones at the base of the upper Griquatown beds. It is also separated from an upper manganese horizon by banded ironstones.

The field relationships can be studied in the quarries recently opened. The ore of the lowermost horizon in quarries several miles apart has similar lithological features but some mineralogical differences.

On the farm Annex Langdon, surface relief is only a few feet. The whole area is almost entirely covered by calcrete or Kalahari sand that lies as residual portions of scrub-fixed dunes. The sand cover over the older formation is thin, and banded ironstones crop out at surface over an area of a few square yards. At the time of my visit in July, 1956, the manganese ore underlying the sand and banded ironstones had been exposed in boreholes, pits and the main quarry.

The superficial deposits consist of a ferricrete up to 4 feet thick overlain by 2 to 12 feet of sand, in which artifacts have been found. These deposits rest on a planed surface of manganized rocks. The quarry faces show a succession of manganized sediments gently tilted to an average angle of 15 degrees west (Fig. 4). The dip varies from 12 to 18 degrees but local undula-

tions of up to 23 degrees occur. The strike varies a few degrees only from north-south. There is no intensive folding. Vertical cracks similar to contraction fissures with no vertical displacements, are exposed in the quarry. Near the sub-outcrop of the manganese ore and footwall ironstones, a small fault with a little brecciation was seen, and here and there displacements of fractions of an inch occur.



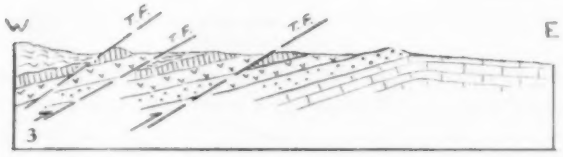


FIG. 2. Geological sketch map of the Kuruman manganese field, showing the distribution of the pre-Karroo formations below younger rocks as inferred from borehole data, magnetometric anomalies and rare outcrops (modified from Kupferbürger *et al.*) (4).

FIG. 3. Schematic section of pre-Karroo geology, along an east-west line near Black Rock-Hotazel. T.F. = Thrust fault.

In the eastern part of the quarry the manganized ore rests with a clean contact on a high-grade banded red hematite, probably resulting from banded ironstone of the basal part of the upper Griquatown beds. Banded ironstones, preserved just south of the quarry, cap the manganese horizon, but the actual

contact with the hanging wall was not seen in the quarry. The thickness of the manganized sediments is just over 70 feet.

The strata vary in appearance from "shaly" to coarser bedded layers. Much of the ore in the exposed faces is massive, dull, dark brown and streaked with thin, brighter grey-black to dark steel-grey bands and lenses. Some ore with fine, almost oolitic banding has a flinty conchoidal fracture. The ores are, however, generally fine-grained.

Down dip away from the sub-outcrop and also towards the base of the formation, particularly in the floor of the quarry, the rock is porous, finely laminated, and breaks into tabular "slaty" fragments. Near the surface, pockets of heavy, shiny, finely crystalline ore, obviously surface enriched, are found.

Veins of calcite traverse the ore. Thin veins of cross-fiber cryptomelane are parallel to or cut across the bedding. Small nests of soft, felty, purple-brown cryptomelane fibers and vugs lined with small crystals of quartz, and goethite pseudomorphous after hematite have been seen.

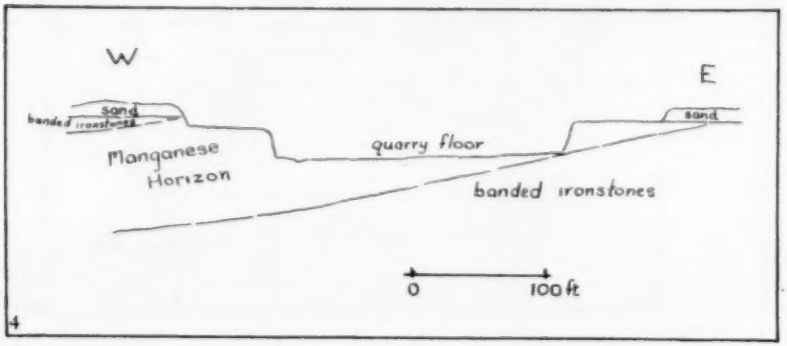


FIG. 4. Annex Langdon. Cross section of quarry, July, 1956.

On the farm Smartt, the quarry faces show the same general features observed at Annex Langdon. There is much more dull, dark-brown ore with less of the shaly and finely "oolitic" varieties. Vertical fractures are filled with brecciated ore and calcrete, no doubt derived in part from surface. Within the manganized sediments there are conspicuous seams of cross-fiber cryptomelane, which near surface is replaced by cross-fiber pyrolusite. There are also thin calcite veins within the ore body.

The footwall resembles a partially manganized limestone near surface, particularly within the quarry away from the sub-outcrop. Kupferbürger (4) has recorded that deep borehole intersections away from sub-outcrop show progressively poorer ore, which finally becomes laminated manganiferous limestone. As at Annex Langdon, the ores lie below a sand cover that varies from 10 to 30 feet in thickness.

MINERALOGY OF THE ORES

General

Identification of manganese minerals is not easy in such fine-grained ores. In addition to hand specimen examination, detailed studies of optical properties and etching tests on polished sections supplemented by chemical determinations, differential thermal analysis and X-ray powder photographs, were made.

The ores are clearly separable into a few distinct types, of which two or

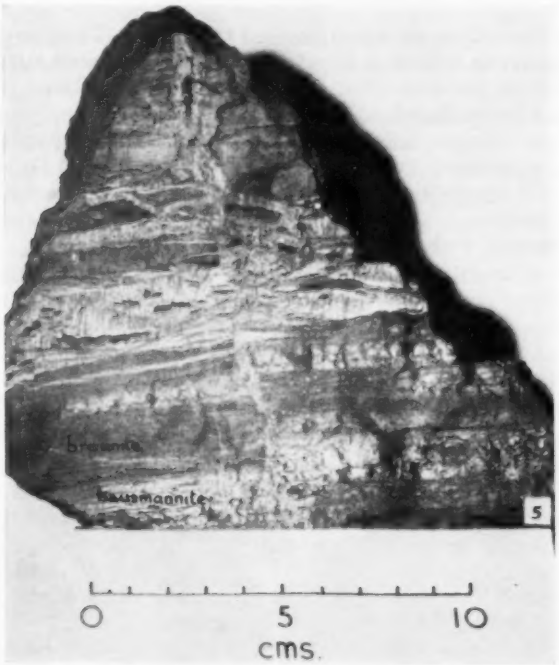


FIG. 5. Hand specimen of bedded manganese ore from Smartt quarry. It contains seams of cross-fiber cryptomelane, bands of bright dark-grey hausmannite and of dull-brown braunite. There is a small displacement down the middle of the specimen cemented by cryptomelane.

more may be found within a single hand specimen (Fig. 5). The dominant types are (1) braunite and (2) cryptomelane-rich ores. Both varieties are somewhat porous and contain calcite in veinlets or as small scattered single crystals. There are also (3) thin bands or lenses of hausmannite in braunite ore, (4) heavier crystalline masses of hausmannite, and (5) small "boulders" of highly magnetic jacobsite ore. Types 4 and 5 lie near the top of the deposits below the sand cover. (6) There are also the dull brown or steel-grey

cross-fiber veins that lie parallel to or across the bedding of braunite-rich ore. (7) The partly manganized siliceous, and in places somewhat calcareous footwall should also be noted.

Braunite ores are characterized by the presence of silica, but cryptomelane ores hold significant amounts of combined water and alkalis, so that chemical determinations of these constituents afford a means of confirming hand specimen or microscopical identifications.

Microscopical Features

Braunite Ore.—This ore is characterized by small voids and irregular areas that polish poorly on billiard cloth. It is composed dominantly of a braunite that has a distinct lilac-brown tint under the oil immersion lens. The poorly polished areas are reddish-brown in color and may be earthy cryptomelane. There are lighter-colored psilomelane or cryptomelane specks and laths 1 to 2 microns in size, and very thin veinlets, in the braunite. Thin blades of magnetite up to 0.1 mm long with some hematite are present. Calcite in small patches is common.

Partial chemical analyses on a number of specimens gave:

	%	
SiO_2	6.3 to 7.0	
Fe_2O_3	12.33	(one determination)
K_2O	0.15 to 0.4	
Na_2O	0.25 to 0.5	
H_2O+	1.2 to 2.0	
CO_2	5.1 to 10.0	

All the silica is in combination in the braunite. When the powdered ore is dissolved in hydrochloric acid, gelatinous silica is left, but no quartz grains. The iron content cannot all be accounted for by the small amount of magnetite and hematite. The braunite probably holds some iron, although not enough to make it a ferrian braunite. X-ray patterns are identical with that of normal braunite.

Specific gravities of 3.64 and 3.9 on coarsely crushed specimens clearly indicate the presence of calcite and voids in the ore.

Cryptomelane Ore.—This type of ore is more abundant on the Annex Langdon property. It is essentially fine-grained, shale-like or "oolitic." Under the microscope it is steely grey and predominantly isotropic. Granules are 0.1 mm diameter, and circular areas (oolites?), 0.3 mm diameter. The cryptomelane clearly shows replacement of earlier minerals in most of the sections examined. Small cubes of magnetite, 8 microns square, fresh or partly altered to martite, appear to be of early formation and are sparsely scattered in the ore. Hausmannite relicts are common; those of braunite are rare. Pyrolusite blebs or "rosettes" 3 to 8 microns diameter, and veinlets 2 to 6 microns wide, are widespread. Between crossed nicols this pyrolusite is revealed as an anisotropic mesh of fine, felty laths. Hematite occurs as long thin veins 2 microns wide, while crystals 12 microns in diameter, show characteristic pale blue-grey color and red internal reflection, in oil.

Within the cryptomelane ores are patches of calcite and of a manganese mineral, probably a wad, which does not polish well.

Chemical determinations made on specimens known to be composed essentially of cryptomelane gave:

	%
SiO_2	0.25
K_2O	0.8 to 1.7
Na_2O	1.0 to 1.6
H_2O+	4.5 to 8.1
CO_2	trace to 0.4

Specific gravities of 3.97 to 4.04 obtained on the cryptomelane ores indicate that this ore is more compact and contains less gangue or voids than the braunite ores.

Some cryptomelane specimens contain significant amounts of hausmannite, much of which has been replaced by the cryptomelane.

Hausmannite Bands and Lenses.—Bright bands and lenses a few tenths to 3 inches in thickness, parallel to the bedding, are conspicuous in the braunite ore. Under the microscope, they show an interlocking aggregate of hausmannite grains, some twinned, of 8 microns average diameter. Sparsely scattered irregular patches of cryptomelane and pyrolusite a few microns in diameter lie in the hausmannite. A typical specimen has 0.95 percent of combined water and specific gravity of 4.66. Generally, however, these hausmannite bands have been extensively replaced by cryptomelane, although this is not easily recognizable in the hand specimen (Fig. 6). Such replaced bands have a lower specific gravity, 4.04 to 4.12; rather more combined water, 4.4. to 6.0 percent, with significant amounts of alkalis—potash 0.8 and soda 1.25 percent.

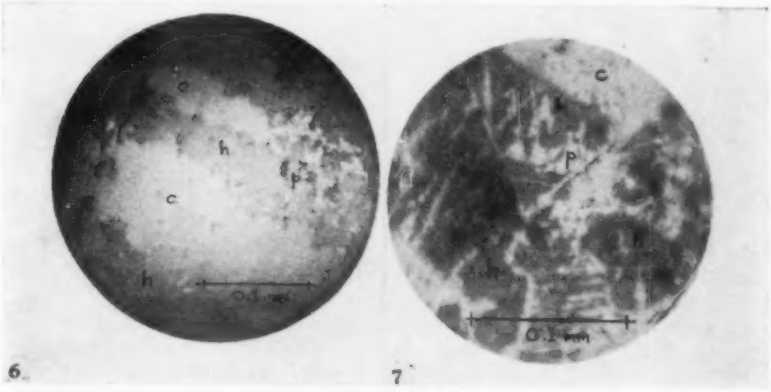


FIG. 6. Cryptomelane (c) and later pyrolusite (p) replacing hausmannite (h). Annex Langdon.

FIG. 7. Cryptomelane (c) and pyrolusite (p) replacing hausmannite (h) in surface enriched ore. Hotazel.

Dr. F. A. Raal reported the following measurements made on an X-ray photograph taken with Mo radiation:

Measured	A.S.T.M. Cards Hausmannite	Cryptomelane
4.82	—	4.84
3.09	3.08	3.097
2.76	2.76	—
2.405	—	2.40
2.15	—	2.149
1.55	1.55	1.55
1.46	1.47	—
1.38	1.38	—

He concludes that although some of the hausmannite spacings are missing, the sample is a mixture of hausmannite and cryptomelane. This supports the microscopical and chemical data. A little pyrolusite may replace the cryptomelane.

Hausmannite Masses at Sub-outcrop.—Heavy, dull to brighter, dark masses at sub-outcrop below sand on both manganese horizons are known to be high-grade ore. They are slightly magnetic. Specimens from the lower horizon contain:

	%
Mn	56
H_2O+	1.3
K_2O	0.5
Na_2O	0.05

Specific gravity 4.94.

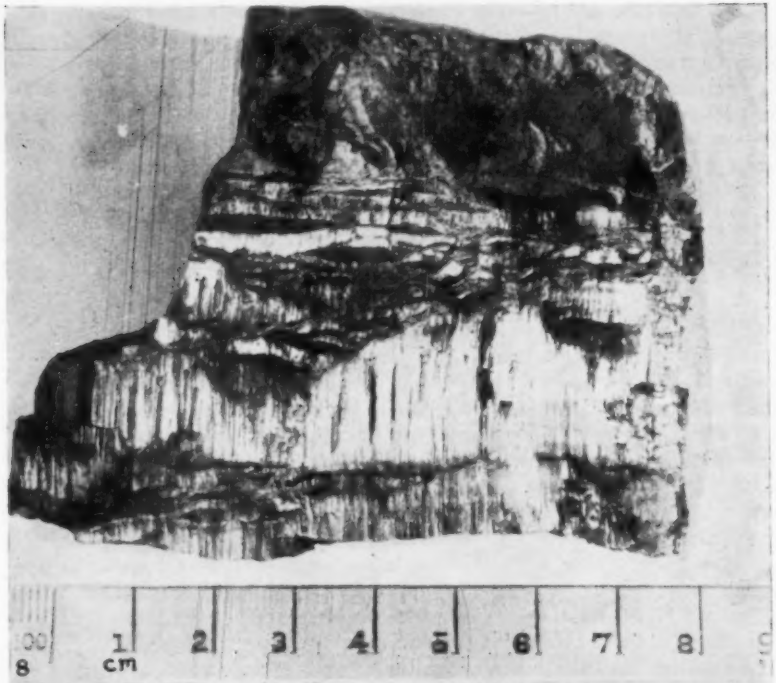
Sub-outcrop ore taken from borehole cores in the upper horizon have:

	(1) %	(2) %
Mn	48.8	55.6
Fe_2O_3	19.6	10.76
SiO_2	1.2	0.4
H_2O+	2.58	1.84
Specific gravity	4.48	4.62

(1) From sub-outcrop immediately below 74′ of sand.
(2) Three feet below sub-outcrop.

Under the microscope these ores are rather more crystalline than the other varieties described above. Hausmannite is the predominant mineral, often characteristically twinned, with typical red internal reflection under oil. It is replaced by psilomelane or a little cryptomelane, as well as by pyrolusite which cuts across it in thin veinlets. Hematite crystals 4 to 8 microns in diameter, are scattered through the sections. Magnetite cubes from 4 to 24 microns square may have hematite borders. Small amounts of granular cryptomelane, 16 microns across, and small lilac-brown patches, probably braunite, are also seen.

Hausmannite is partly replaced by pyrolusite along cleavage planes, and what appears to have been braunite originally is now replaced by cryptomelane (Fig. 7).



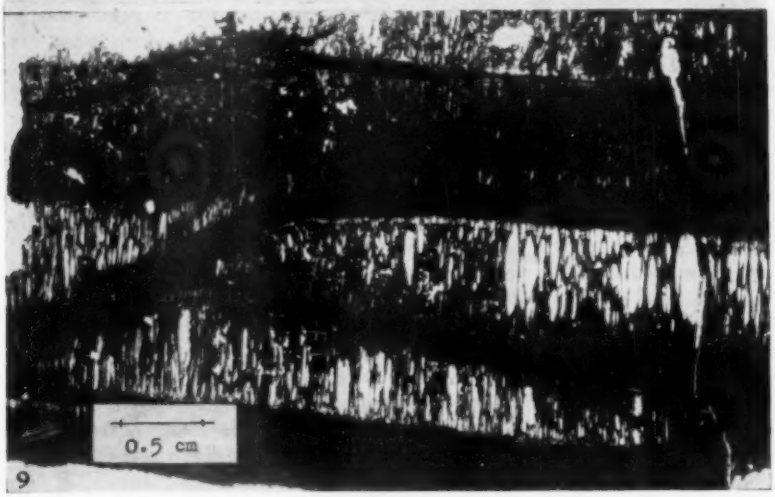


FIG. 8. Hand specimen of cross-fiber seams of cryptomelane, Smartt Mine.
FIG. 9. Thin section of cross-fiber cryptomelane (opaque) cut at right angles to the bedding. Clear areas are calcite.

Jacobsite "Boulders."—These are rare, and so far only noted from the subcrop at Annex Langdon. The masses are heavy, dull greenish-grey in color, and strongly magnetic. Microscopical examination reveals that jacobsite is dominant with some euhedral twinned hausmannite. The two minerals do not seem to have the intimate association as in true vredenburgite; they are distinctly granular and separate. Cryptomelane and rather more pyrolusite in "moth-eaten" areas and veinlets are present.

Partial analysis gave:

	%
Fe_2O_3	46.41
K_2O	0.85
Na_2O	0.3
H_2O+	1.13

Specific gravity 4.67.

Fibrous Cryptomelane.—The seams of dull-brown cross-fiber that look so much like replaced asbestos fiber are a fascinating mineralogical curiosity. They are fairly abundant at Smartt but rather rare on Annex Langdon. They occur singly or as groups separated by thin partings of ore, varying from fractions of an inch to 2 inches in width, and are generally parallel to the bedding, although they may cut across it (Fig. 5).

In hand specimen they exhibit features similar to those found in crocidolite asbestos seams. Thin bands of dull, brown, fine-grained ore pass obliquely across the seams and simulate the partings of magnetite in crocidolite seams (Figs. 8, 9). In the deeper parts of the quarries the cryptomelane fibers are dull and dark brown, with calcite making up much of the seam. At the top of the deposit near the contact with the overlying sand, fibers are steel-grey pyrolusite, apparently pseudomorphous after cryptomelane, and are separated by a dark brown-black mineral replacing calcite. In these seams there are cavities filled with earthy brick-colored material and small granules of quartz. At intermediate depths in the quarry the cryptomelane fibers are only partially replaced by pyrolusite.

Thin section examination clearly shows that the cryptomelane fibers have replaced calcite in seams of earlier formation, and there is evidence that some calcite crystallized later, between the fiber terminations and the containing rock. The fibers are commonly translucent, light brown in color and very slightly pleochroic. Sections cut vertically across the veins show that these fibers have grown out from the vein margins to replace the calcite in a manner that leaves oval and elongate patches of the carbonate (Fig. 9). Individual calcite grains may be separated by fibers but are in optical continuity. The texture of these partly replaced calcite veins is exactly the same as that of veins free of fibrous mineral. The appearance of some of the structures is reminiscent of wood cells, and typical of low temperature deposits (Fig. 10). Sections cut parallel to the contacts show that the fibers in cross-section are wrapped around oval or rounded "cores" of calcite (Fig. 11). Thin sections of the harder silvery-grey pyrolusite fiber seams are completely opaque—all the calcite has been replaced—and there are only a few grains of chalcedonic silica.

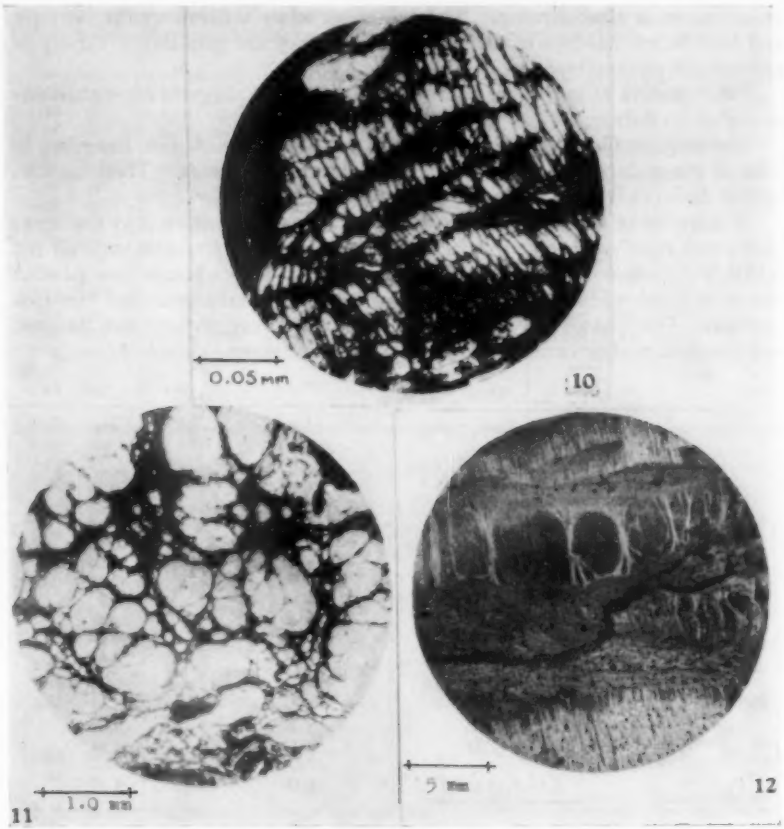


FIG. 10. Thin section of fibrous cryptomelane-calcite seams, showing "wood-cell" structure. Plane polarized light.

FIG. 11. Thin section of fibrous cryptomelane-calcite seam, cut parallel to seam contacts. Plane polarized light.

FIG. 12. Polished section of seams of fibrous pyrolusite pseudomorphous after fibrous cryptomelane.

It was not possible to prepare satisfactory polished sections of the soft cryptomelane fiber seams, but the harder steel-grey pyrolusite fibers take an excellent polish. Under the ore microscope the arrangement of the pyrolusite fiber bundles is identical to that of the cryptomelane fibers in the calcite-fiber veins as seen in thin section, so there is no doubt that this is an example of perfect pseudomorphism by pyrolusite after cryptomelane (Fig. 12). The pyrolusite fibers, each one micron or less in diameter, exhibit an intense anisotropism in longitudinal sections. In cross-sections of the fibers, however, the

anisotropism is much weaker. The dull areas between fibers appear isotropic and have a reddish-brown internal reflection; they are probably a variety of psilomelane or cryptomelane.

Fiber growth in individual seams is composite and suggests more than one period of formation.

Not only do the fibers occur in seams, but also as on Annex Langdon, in tufts of purplish-brown flexible needles projecting into vugs. These needles have a moderately high refractive index and are length slow.

A quantity of the softer, brown fiber seams was broken up into fine fragments and repeatedly treated in acetic acid of moderate strength until all the calcite had dissolved. After much water-washing, the carbonate-free powder was oven-dried. Hand-magnet treatment removed small amounts of iron-rich material. Portions of the sample were sent for X-ray, differential thermal, and chemical analyses and the results obtained are given in Table 1.

TABLE 1

	1	2	3
SiO_2	0.61	absent	0.18
TiO_2	0.00	—	none
Al_2O_3	0.25	0.98	0.39
Fe_2O_3	0.92	3.42	0.19
MnO_2	77.66	79.94	87.09
MnO	8.22	6.09	2.49
MgO	0.35	0.16	0.07
CaO	0.79	absent	none
Na_2O	1.95	0.74	0.48
K_2O	1.53	5.95	3.10
H_2O+	7.48	0.36 (above 120° C)	3.58
CO_2	trace	—	—
BaO	0.07	2.76	none
	99.82	100.40	99.94
	S.G. 4.19 at 20° C	4.35	4.17

1. Cleaned cryptomelane fibers. Locality, farm Smartt, Kuruman district, South Africa. Analysis on sample dried at 105° C. Analysts—McLachlan and Lazar (carbon dioxide by L. Tonetti).

2. Cryptomelane from Sitapar, Central Provinces, India. ZnO, CoO, WO_3 and P_2O_5 absent (7).

3. Cryptomelane. Total includes CoO, 0.08; ZnO, 1.69; H_2O-, 0.60 (10).

This new analysis resembles analyses of cryptomelane published previously. The water content above 105° C has been shown to be nonessential in the structure (10) and probably behaves like zeolite water (3). The analysis was brought to a water-free basis and the formula calculated using 16 O to the unit cell is $Mn^{4+}_{7.08}(Mn^{2+}_{0.92}Ca_{0.11}Mg_{0.07})(K_{0.26}Na_{0.5})O_{16}$. Silica, alumina and iron oxide of small amount, have been regarded as admixed impurities.

This formula compares well with that given for analysis 2 quoted above.

$$Mn^{4+}_{6.99}(Mn^{2+}_{0.65}Al_{0.15}Mg_{0.02}Na_{0.18})(Ba_{0.14}K_{0.96})O_{16}$$

TABLE 2

1		2		3		4		5		6	
9.61	vs	9.65	vs	9.37	s					9.7	60
7.04	w	7.05	ms	7.02	s	6.92	20	6.98	40		
6.56	w	6.56	m								
		4.92		4.96	ms	4.91	20	4.97	30		
4.78	s(Br)	4.79	s(Br)					4.84	50	4.85	60
4.44	m	4.42	m							4.48	100
4.20	m	4.20	m	4.15	w						
		3.52	vw	3.52	w	3.47	10	3.514	10		
								3.454	20		
										3.22	80
3.11	w	3.12	w	3.12	s	3.11	60	3.149	30		
								3.110	80		
3.00	vw	3.02	vw					3.097	30		
2.76	w	2.76	w	2.71	ms			3.065	20		
2.58	w										
2.45	ms	2.45	m							2.59	60
						2.46	10	2.481	30	2.5	60
2.40	ms	2.40	s	2.40	w			2.425	10		
2.35	ms	2.36	m			2.40	100	2.399	100		
2.20	w	2.22	m					2.366	5		
2.17	w	2.16	m	2.20	w	2.21	20	2.194	40	2.23	60
				2.15	w	2.16	20	2.170	30		
2.21	w							2.149	30		
1.98	w	1.98	w							2.1	40
1.92	w	1.92	w								
		1.84	w	1.84	vw	1.84	60	1.843	40	1.93	40
								1.820	50		
1.77	w	1.77	vw								
1.74	w							1.745	10		
								1.723	10	1.72	40
1.66	w			1.66	vw			1.684	10	1.67	60
1.65	w	1.64	vw			1.64	20	1.654	80		
1.54	w	1.54	w(Br)	1.55	vw	1.54	60	1.553	10	1.51	60
								1.535	20		
1.43	w	1.43	ms	1.43	vw	1.43	20			1.49	40
1.41	w	1.41	w								
						1.35	60				
1.39	w	1.39	w								

1. Fine purplish-brown fibers from vug in manganese ore. Farm Annex Langdon.
2. Fibers freed from calcite by hand-picking. Farm Smartt.
3. Finely powdered fibers from acetic acid digestion. Analysed specimen. Farm Smartt.
4. Cryptomelane. Ramsdell, Amer. Min., v. 27, 611 (1942), A.S.T.M. card No. 6-0547.
5. Cryptomelane. Mathieson and Wadsley, Amer. Min., v. 35, 99–101 (1950), A.S.T.M. card No. 4-0774.
6. Montmorillonite (anhydride) Bradley and Grim, Amer. Min., v. 36, 182 (1951), A.S.T.M. card No. 7-304.

Mathieson and Wadsley (7) suggest that the ideal formula is $K_2Mn_8O_{17}$ and that potassium is probably distributed at random and not of fixed amount. The best formula for the new analysis given above is $KRMn_7O_{16}$.

In 1932 Ramsdell (9) showed that psilomelane has two structures, the one high in barium, the other holding potassium with little or no barium, named cryptomelane and later said to be more common than psilomelane (10).

The National Physical Research Laboratory, Pretoria, report that the d-

spacings of Debye-Scherrer patterns listed in Table 2 were measured on photographs taken in a 114.59 mm camera using Mn-filtered Fe-radiation. Exposure times ranged from 16 to 23 hours. No shrinkage corrections could be applied but the error should not be more than 0.2 percent.

Good agreement was found between some of the measured values and the d-spacings given by Ramsdell and by Mathieson and Wadsley. Additional lines on all the photographs might possibly be due to montmorillonite anhydride, which, if present, can only be of very small amount.

The D.T.A. diagram (Fig. 13) is quite unlike those published for cryptomelane (5). Dr. T. L. Webb suggests that the exothermic effect between 100° and 200° C may be due to oxidation of some constituent.

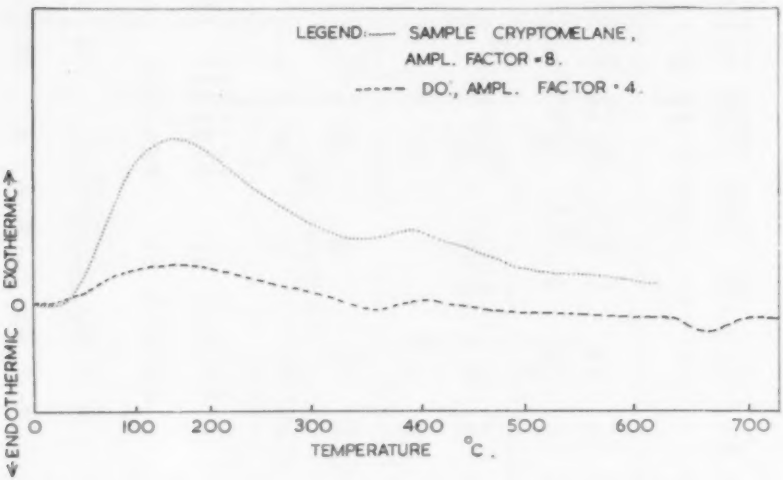


FIG. 13. Differential thermal analysis curve of fibrous cryptomelane.

Manganized Calcareous Footwall.—On Annex Langdon the footwall and hanging wall are typical red hematite iron ore and banded ironstone, respectively. On Smartt the fine-grained hanging wall has the appearance of a manganized banded ironstone in hand specimen. Under the microscope, however, it is composed of braunite with replacing pyrolusite, cryptomelane and psilomelane. It also contains calcite and quartz grains. A partial chemical analysis gave:

	%
SiO_2	6.40
Fe_2O_3	2.94
CaO	12.79
H_2O+	2.00
CO_2	12.20

The footwall is a hard, faintly bedded, dull black rock. Calcite is present in thin bands and lenses up to 5 mm thick, and as scattered small crystals. The rock has the appearance of a manganized carbonate rock. Microscopic examination shows that braunite, the predominant mineral with some replacing cryptomelane, is traversed by thin pyrolusite veins up to 45 microns wide, also associated with the calcite. There are thin veins of psilomelane or cryptomelane, small specks of hematite 2 microns across and traces of magnetite. The carbon dioxide content of typical specimens was found to be 9.8 and 10.6 percent, corresponding to 22.3 and 24.2 percent of calcite.

The manganese minerals in the rock, freed of calcite by acetic acid treatment contained 8.92 percent of total silica and 1.96 percent combined water. After digestion of the rock in hydrochloric acid the residue was gelatinous silica with only a few quartz granules. This confirms the predominance of braunite with much less of cryptomelane. Semi-quantitative tests revealed traces of both alumina and magnesia.

ORIGIN OF THE MANGANESE DEPOSITS

Although these manganese deposits lie along the northward extension of the thrust faults and the strike of the Postmasburg manganese ores, their geological associations are entirely different from those at Postmasburg.

It has been concluded that the manganese ores of the Postmasburg area were formed mainly during a period of uplift and erosion subsequent to the post-Loskop folding, thrusting and cataclasis. Metasomatic replacement of breccias and Gamagara conglomerates and shales by circulating waters under atmospheric conditions, produced the ores so closely associated with the dolomitic limestones of the Transvaal System. du Toit (2) and Nel (8) consider that these limestones that contain over one percent of manganese dioxide, were the source of the manganese. Extensive brecciation during the post-Loskop orogenic period permitted weathering and rapid dissolution of the limestones, and released manganese which was subsequently precipitated and concentrated in the siliceous, argillaceous and cataclastic rocks. de Villiers (1) suggests, however, that the mineralizing solutions were partly magmatic, basing his conclusion on the ore textures and the presence of elements such as lithium, sodium, boron and fluorine.

In the Kuruman area, the westerly dipping manganized rocks are part of the Upper Griquatown beds that overlie andesitic lavas.

Quarrying and drilling have shown that the highest grade ores (hausmannite-rich) are at or near the sub-outcrop, and that in depth along dip, the manganese content decreases until the ore becomes a highly manganiferous bedded limestone. It may be inferred, therefore, that the original sediment was a limestone containing some manganese. This limestone horizon contained little magnesia, unlike the older dolomitic limestones of the middle member of the Transvaal System. Dr. Boardman (verbal communication) has suggested that contemporaneous erosion during and after gentle folding of the Campbell Rand limestones to the east, could have provided some of the material of the Upper Griquatown limestone horizon. Manganese from the Camp-

bell Rand rocks dissolved in carbonated waters, was later precipitated in the form of pyrolusite or as the hydrous oxide mixture "wad" by oxidation in the younger limestone. The precipitate, a "gel" capable of absorbing alkali ions, would later crystallize.

There were varying amounts of silica in the limestones, and layers of pure calcite alternated with others containing silica, either detrital or of chemical origin.

The Upper Griquatown period of deposition was followed by gentle folding and erosion of the banded ironstones, manganiferous limestones, and lavas. Migration and concentration of manganese probably under atmospheric conditions continued thereafter. Potassium and sodium ions derived from the andesitic lavas not more than one hundred feet below the lower manganese horizon, could have been absorbed by the wad from circulating waters at this stage. Lithium and barium are present as traces in the ores, although lithiophorite may be present in small amounts in the upper horizon, and suggests slightly more lithium. Thus the alkali elements in the ores need not have been brought in by magmatic waters.

It is likely, therefore, that the limestones carried significant amounts of manganese prior to the Gamagara sedimentation. The original pyrolusite and wad were recrystallized and the latter dehydrated under diagenesis resulting from deep burial after the Loskop (Gamagara) deposition. Hausmannite in the purer calcite layers, and braunite and hausmannite in the strata containing silica, were formed under reducing conditions and at temperatures perhaps less than 500° C. There could also have been some migration of silica from the conversion of braunite to hausmannite under such conditions (6, p. 141). Bixbyite (sitaparite) was not identified with certainty in the specimens examined, and may not have developed to any great extent because the temperatures reached were not quite high enough.

It is not clear when cryptomelane, so abundant in certain areas, was formed —whether it was present from the first stages of mineralization, or whether it was an alteration product of hausmannite at times when alkali-bearing solutions circulated through the limestones. Mathieson and Wadsley (7) suggest that the mineral may form from a manganese dioxide mineral with intrusion of potassium ions. Substitution of ions causes distortion in the lattice and the only direction in which strain does not hinder growth is parallel to the c axis. This would explain the fiber growth in calcite veins. Water is absorbed slowly and probably behaves like zeolitic water. Cryptomelane is stable to temperatures near 520° C above which it changes to cubic Mn_2O_3 (bixbyite) (3). Cryptomelane ores and fibrous seams together with other manganized layers displaced by small faults were recemented by later cryptomelane and pyrolusite (Fig. 5). If cryptomelane formed early in the history of the deposits, temperatures would rarely have been higher than 520° C thereafter (3). It is not known at what stage magnetite crystallized, but its mineralogical associations show that it developed earlier than the manganese minerals now present in the ore. Jacobsite formation may have been contemporaneous with that of near-surface hausmannite enrichment.

There is some iron enrichment in the banded ironstone footwall near sub-outcrop of Annex Langdon, but significant enrichments of banded ironstone like that of the manganiferous limestone in the area, have not yet been observed.

The continuous, although somewhat flexed manganized horizons were broken into several separate blocks and wedges by the post-Loskop thrusting that cut obliquely across from the west. Some of these blocks, truncated on the west by the thrust planes and overridden by younger Gamagara rocks, were included in allochthonous masses. The more easterly wedges in the autochthonous mass were in turn overridden by the older, Lower Griquatown rocks (4) (Fig. 2). There is no evidence available at present to show that this thrusting affected manganese concentration.

Near-outcrop enrichment must have taken place during the subsequent heavy erosion of the separated smaller masses and long strike sections of the manganese horizons. Hausmannite was extensively replaced by pyrolusite under these conditions. There was further deep burial after the deposition of the Dwyka tillite and overlying shales, on a surface which was already highly enriched. This enrichment is shown by a drill intersection through the tillite-ore contact at a depth of 900 feet below present surface (4).

Extensive erosion followed the Karroo cycle of deposition, the pre-Dwyka topography was to some extent resurrected, and there was probably further near-surface enrichment. Replacement of fibrous cryptomelane by pyrolusite in seams just at sub-outcrop, may date from this period. Later the Kalahari rocks and sands covered the older topography, including the manganese outcrops, completely. Some migration of manganese is still taking place under atmospheric conditions below the Kalahari cover.

From the above outline of the geological history and mineralogical changes, it is concluded that the ores in the limestones were not produced by magmatic waters but by the action of circulating meteoric waters.

MINING ASPECTS AND GRADE OF ORE

Kalahari deposits blanket the entire area in which the manganese ores lie and outcrops such as the conspicuous Black Rock are rare. Exploration carried out by magnetometric surveys and drilling has traced the manganese horizons below the cover of younger rocks (4), and has demarcated the areas in which the Gamagara and Karroo rocks had been removed by erosion from the manganese horizons in pre-Kalahari times. It is in these areas where the manganese and associated banded ironstones lie immediately below the Kalahari deposits, that mining of the ores is at present being undertaken.

The interbedded manganese, with gentle dip, is fairly uniform in thickness and continuous along dip and strike except, of course, where it has been thinned by erosion or has been cut across by thrust faulting. It offers a contrast to the ore bodies of the southern fields around Postmasburg, which are commonly irregular in shape, occur in other formations, and lie on uneven floors of dolomitic limestone.

The Kalahari cover of clays, calcrete, and sand dunes over the manganese sub-outcrop is commonly relatively thin. In the case of the deposits on Annex Langdon and Smartt, there is an average cover of about 12 and 25 feet respectively, but on Hotazel the sand is somewhat thicker. Sand and calcrete up to 20 feet thick over the ore-bodies can be removed cheaply by ordinary tramming methods. Slightly greater thicknesses can be dealt with by fleets of Tournapulls. Quarrying methods of mining can then be employed. Under thicker cover, the ores can only be won by underground methods.

The physical properties of the ores are excellent from both the mining and transport aspects. Although they fracture easily, they are hard enough to stand up well to handling when railed or shipped. Drilling with tungsten carbide bits and judicious use of explosives reduces unsaleable fines to insignificant amounts. Large blocks are broken down to six-inch size by a sledge hammer.

The mineralogical studies have shown that the composition of ore over a reasonable vertical thickness, strike length and for some distance down dip, is fairly consistent in any one locality. This is substantiated by systematic assay of shipments and stockpiles. A uniform grade can be maintained relatively easily, lower grade ore being eliminated by selective mining or by hand-sorting, which is efficiently done by Non-European labor.

A representative sample taken from a very large shipment of ore from Annex Langdon gave the following analysis shown in Table 3.

TABLE 3

(Sample dried at 105° C)

	%			%
MnO_2	72.71	Mn 49.61	SiO_2	1.13
MnO	4.73		P_2O_5	0.04
Fe_2O_3	10.38	Fe 7.26	CO_2	0.40
Al_2O_3	1.20		H_2O+	4.30
BaO	0.72		Cu	0.006
CaO	0.81		S	0.003
MgO	1.00	As 0.00004%	Bi	0.01
Na_2O	0.29	TiO_2, Zn, trace		
K_2O	3.22	V_2O_5, Li_2O, Cr, Ni, Co, Pb, Mo, W, all 0.00%		100.949

Analysts—Messrs. McLachlan & Lazar.

This bulk composition is similar in many respects to the composition of the pure cryptomelane, and it shows, therefore, that the ore contains a very high percentage of that mineral.

A much later shipment analyzed 49.38% Mn and 7.36% Fe and reflects the uniformity of the average grade (almost run of mine). The lowest grade ores are generally somewhat friable and rich in calcite, with a manganese content between 21.7 and 35.8 percent.

Braunite-rich ores seem to be associated with considerably more calcite than the hausmannite or cryptomelane varieties, which on the other hand hold significant amounts of water and alkalis. This makes the ore a fine self-fluxing variety, but it reduces the metal content and adds to shipping costs.

The amounts of iron (mainly magnetite with some hematite) increases significantly in certain enriched zones. Unfortunately, the fine-grained nature of the ore makes beneficiation by a cheap simple process such as magnetic treatment, impossible.

Good all-weather roads are made from Kalahari calcrete laid on the sand, and movement of ore from mines to railhead is steady, except during the periods of torrential rainbursts.

The distance from Sishen railhead to Durban, the port of shipment, is about 780 miles. An alternative shipment port, it has been reported, will be available at Port Elizabeth, 660 rail miles from Sishen, which is to be equipped to handle massive manganese ores.

The scale of operations on manganese mines in the area is to a large extent influenced by the number of trucks the Railway Administration is able to place at the disposal of the producers. The carrying capacity of the line from the railhead at Sishen in the iron-rich area, is limited, and a quota system has been devised, allocations being made by a Committee appointed for that purpose.

In conclusion it can be confidently stated that the potential ore reserves in the Kuruman manganese field far exceeds that of the extensive deposits of the Postmasburg area, and it is anticipated that mining activity will continue to expand in the area.

Department of Geology and Mineralogy,
University of Natal, Durban, South Africa,
Nov. 21, 1957

REFERENCES

1. De Villiers, J. E., 1945, The origin of the iron and manganese deposits in the Postmasburg and Thabazimbi areas: Geol. Soc. South Africa Trans., v. 47, p. 123–135.
2. Du Toit, A. L., 1933, The manganese deposits at Postmasburg, South Africa: Econ. Geol., v. 28, p. 95–122.
3. Gruner, J. W., 1943, The chemical relationship of cryptomelane (psilomelane), hollandite and coronadite: Amer. Mineralogist, v. 28, p. 497–506.
4. Kupferbürger, W., Boardman, L. G., and Bosch, P. R., 1956, New considerations concerning the manganese ore deposits in the Postmasburg and Kuruman areas, Northern Cape Province, Union of South Africa: 20th Internat. Geol. Congr. Mexico.
5. Mackenzie, R. C., 1957, The oxides of iron, aluminium and manganese: Differential Thermal Investigation of Clays, Chapter XII, p. 299–328, London.
6. Mason, B., 1943, Mineralogical aspects of the system FeO—Fe_2O_3—MnO—Mn_2O_3: Geol. foren i. Stockholm., Bd. 65, p. 97–180.
7. Mathieson, A. McL., and Wadsley, A. D., 1950, The crystal structure of cryptomelane. Amer. Mineralogist, v. 35, p. 99–101.
8. Nel, L. T., 1929, The geology of the Postmasburg manganese deposits and the surrounding country: Dept. Mines, Pretoria, Geol. Surv. Sheet Explanation.
9. Ramsdell, L. S., 1932, An X-ray study of psilomelane and wad: Amer. Mineralogist, v. 17, p. 143.
10. Richmond, W. E., and Fleischer, M., 1942, Cryptomelane, a new name for the commonest of the psilomelane minerals: Amer. Mineralogist, v. 27, p. 607–610.
11. Visser, D. J. L., 1945, Stratigraphic features and tectonics of portions of Bechuanaland and Griqualand West: Geol. Soc. South Africa Trans., v. 47, p. 197–254.

Economic Geology
Vol. 53, 1958, pp. 598–616

SULFUR ISOTOPES AND THE ORIGIN OF SANDSTONE-TYPE URANIUM DEPOSITS [1]

M. L. JENSEN

ABSTRACT

An isotopic study of sulfide minerals associated with sandstone-type uranium deposits of the Colorado Plateau and Wyoming indicates S^{32}/S^{34} ratios of these 57 samples varying between 21.93 to 23.32. The majority, however, exhibit ratios that are highly enriched in the lighter isotope compared to the ratio of primordial sulfur that is assumed to be similar in ratio to meteoritic troilites, which vary in ratio from 22.18 to 22.24.

The samples are predominantly pyrite and marcasite, but chalcopyrite, covellite, and bornite are included, even though the sulfide mineral species appears to have no relationship to the specific ratio obtained. There is, furthermore, no indication of a difference between ratios obtained from sulfides collected within uranium ore zones in comparison to ratios of sulfides occurring in either adjacent or distant barren uranium ground. The formations (Triassic to Eocene) from which the samples were collected have no obvious correlation with the ratios, nor does the presence or absence of lignitic, woody, or other carbonaceous matter show any correlation with the ratios.

The relatively broad spread of these high ratio values, especially of those samples collected from one deposit, is very suggestive of hydrogen sulfide derived from anerobic bacteria. It is suggested that sulfate waters (possibly both connate and meteoric in origin) in Mesozoic sediments of the Colorado Plateau area were reduced by anerobic bacteria to hydrogen sulfide when these waters encountered carbonaceous-rich zones that provided an environment and energy source for the bacteria. The hydrogen sulfide may have remained where formed or may have migrated to locales barren of carbonaceous matter, but most likely did both.

At a later date, about 60 to 75 million years ago, ore solutions moving through these more porous and permeable channels encountered the very effective reducing agent of hydrogen sulfide which brought about the concentration of uranium through precipitation of the soluble uranyl ions to relatively insoluble UO_2. At the same time iron (and in some cases copper) sulfate was precipitated as relatively insoluble sulfides.

INTRODUCTION

DURING the summer of 1955, a few specimens of pyrite and marcasite were collected from uranium deposits in the Monticello mining district, San Juan County, Utah. The S^{32}/S^{34} ratios of these samples were subsequently not only determined to be greatly enriched in the lighter isotope but also showed a relatively large spread in ratios determined from even closely-spaced specimens. As these features are not at all characteristic of most magmatic hydro-

[1] Abstract (12) presented before the Society of Economic Geologists Annual Meeting, Atlantic City, November, 1957.

thermal deposits, an origin which is favored by many for the sandstone-type uranium deposits, it seemed logical to attempt a more extensive study of sulfides associated with these deposits with the hope that significant information might be obtained pertaining to their genesis.

During a discussion of these preliminary results, Robert M. Garrels notified me of the extensive suite of sulfides associated with uranium deposits that had been collected for the most part by Robert G. Coleman of the U. S. Geological Survey, upon which samples a minor and trace element study had been made. A significant portion of this study, pertaining to the occurrence of selenium in these samples, has been recently reported by Coleman and Delevaux (5).

Although the suite was no longer complete, Robert G. Coleman very kindly sent me fifty of his samples, the S^{32}/S^{34} analyses of which comprise the results of this study.

Based upon these results, the thesis of this paper is that hydrogen sulfide gas, derived from anerobic bacteria, provided a reducing environment in which sulfide and uranium oxide minerals may have been precipitated from the ore-bearing solutions.

Acknowledgment.—The project has been supported in part by the National Science Foundation Grant 3001, by the Shell Grant for Fundamental Research in Geology, and by Mr. Perry Bass of Richardson and Bass. As previously mentioned, the samples upon which isotopic analyses were performed were obtained almost entirely from Robert G. Coleman, although a few additional significant samples were obtained from Irving M. Breger, Alice Weeks, Robert M. Garrels, and F. W. Christiansen, to all of whom I am very grateful, not only for their assistance in providing samples but in offering helpful aid and critical comments about some of the ideas expressed in this paper.

TECHNIQUES AND PROCEDURES

The sulfide minerals were separated from the associated uranium and gangue minerals by Coleman and Delevaux (5) by a process that they describe as follows: The samples "were crushed fine enough to release the sulfide from the gangue material and then elutriated to remove the clay-size fraction (little or no sulfide was lost in the elutriate). The sulfide was then separated from the gangue by flotation, using a Mayeda cell (13). The advantage of the Mayeda cell is the small quantity of material that can be used. Satisfactory separations were obtained on 10-gram samples containing less than 1 gram of sulfide. The sulfide concentrates obtained from flotation were then centrifuged in bromoform to remove the lighter gangue.

For pyrite and marcasite, further purification of the concentrate was effected by treatment with warm concentrated hydrochloric acid to remove oxidation products and carbonates; when silicates remained the concentrate was further treated with warm hydrofluoric acid. Tests have shown that pyrite and marcasite are unharmed by warm hydrochloric and hydrofluoric acid; however, the other sulfides analyzed, such as galena, chalcocite, and chalcopyrite, were not acid treated. The superpanner was used to effect

further purification with these sulfides. Almost all of the samples analyzed were at least 95 percent pure. X-ray and spectrographic determinations on each sample were made to determine what impurities remained, if any."

The process of separation of sulfides from gangue by use of the Mayeda cell has also been used on many samples in our laboratories with very satisfactory results.

In preparation for the isotopic analysis each sulfide specimen was converted to sulfur dioxide by a standard procedure in which the sulfide was burned in a previously evacuated system at a temperature of 1,000° C in a stream of oxygen from a standard cylinder; the resulting sulfur-dioxide gas was dried by being passed through phosphorous pentoxide and collected in a liquid nitrogen trap before being transferred to a sample flask. The flowage and burning rates were controlled by means of bubble-counters, mercury manometers, and time schedules. The yield and purity of several samples was determined to be satisfactory through isotopic analysis by operation of the mass spectrometer in the analytical mode, during which time a scan was made of all m/e values between 1 to 100. As a further precaution all samples were checked for purity by comparing the mass 66 amplifier output with the same m/e peak voltage output of an equal volume of the standard sulfur dioxide gas.

The instrument used is a double collector Model 21-401 Consolidated Electrodynamics Corporation mass spectrometer. The precision of the results was obtained by a repetitive rapid comparison of the sample ratio to the ratio of a standard sulfur dioxide gas; this cyclic procedure was repeated six times for each sample, which required a minimum time of twenty-four minutes to complete an isotopic analysis consisting of six alternating comparisons of each speciment with the standard gas.

For purposes of comparison with other published S^{32}/S^{34} studies, all ratios are related to the common standard of troilite from the Cañon Diablo meteorite, which has a ratio of 22.21, and the precision of the results is $\pm$ 0.02 in standard deviation or better.

Although S^{32}/S^{34} ratios have been reported almost without exception as ratio values, δ‰ values offer a more rapid visual connotation of the variation of samples from the standard. These values are given with the S^{32}/S^{34} ratios of each sample on Table 1 and are plotted as the abscissa of Figures 1, 2, and 3. The standard for the permil values is still, of course, Cañon Diablo troilite. δ‰ values were calculated from the following relationship:

$$\delta S^{34}{}_{00}^{0} = \frac{S^{32}/S^{34}\ (\text{standard}) - S^{32}/S^{34}\ (\text{sample})}{S^{32}/S^{34}\ (\text{standard})} \times 1{,}000.$$

RESULTS

The ratio results of the samples analyzed are listed in Table 1, both in S^{32}/S^{34} ratios and δ‰ values. The samples are arranged in groups according to the stratigraphic horizon from which the respective samples were collected, and with the exception of the miscellaneous samples, are listed by

TABLE 1

SULFIDES IN SANDSTONE-TYPE URANIUM DEPOSITS

Number[1]	Mineral[2]	Type[3]	Geologic Location[4]	S^{32}/S^{34}	δS^{34} ‰
Sulfides from Jurassic Sediments					
			Morrison Formation		
1	pyrite	O	Uravan District, Montrose County, Colorado North Star mine: mineralized sandstone	22.70	−23.0
5	pyrite	B	Gypsum Valley District, San Miguel County, Colorado Pitchfork mine: sulfide from sheared zone along axis of anticline, associated with native sulfur.	23.12	−41.0
9	pyrite-marcasite	O	Thomsons District, Grand County, Utah Little Eva mine: pyrite as interstitial material associated in part with carbonaceous matter.	23.06	−38.3
11	pyrite marcasite	B	Bull Canyon District, Montrose County, Colorado Mineral Joe mine: pyrite nodule with elongation parallel to the bedding, some oxidation.	22.51	−13.5
12	pyrite-marcasite	B	Mineral Joe mine: euhedral pyrite marcasite nodule collected at bottom of second incline in dark gray clay.	22.73	−23.4
22	marcasite-(pyrite)	O	J.J. mine: sulfide bleb in middle of large black irregular mass of mineralized rock	22.62	−18.5
23	marcasite-(pyrite)	B	J.J. mine: pyrite as nodules and veinlets in green clay bed about two feet thick between ore sandstone beds.	22.52	−14.0
24	marcasite-(pyrite)	B	J.J. mine: pyrite in basal green mudstone near contact with sandstone, finely disseminated as nodular growths.	22.80	−26.6
29	"chalcocite"	O	Slick Rock District, San Miguel County, Colorado Tailholt mine: small elongate stringer in green mudstone; carbonaceous material.	no output	—
42	pyrite	O	Grants District, Valencia County, New Mexico Woodrow Pipe mine: breccia pipe, banded pyrite-pyrite cores show marcasite rims.	22.50	−13.0
50	pyrite	B	Shannon Oil Company claims: sample is composite of several cores from barren Morrison fm below Lakota formation.	21.82	+17.6
			Entrada Formation		
51	marcasite	O	Rifle District, Garfield County, Colorado Garfield mine: vertical sulfide vein with carbonaceous pellets cutting vanadium layer.	21.93	+12.6
			Todilto Limestone		
64	pyrite	B	Grants District, Valencia County, New Mexico F.O. Manol mine: oxidized pyrite in flat discoids in shaly lime horizon, pyrite in central portions is fresh.	22.69	−21.6
Sulfides from Triassic Sediments					
			Chinle Formation		
66	marcasite	O	San Rafael District, Emery County, Utah Lucky Strike mine No. 2: collected at end of small drift away from main mine, occurring as shear plane fillings in green mudstone, petroleum present oozing along fracture.	21.97	+10.8

[1] Sulfide sample number used by Coleman and Delevaux (5).
[2] X-ray identification on analyzed material. Quotation marks indicate impure samples; mixtures are hyphenated with dominant phase listed first, i.e., marcasite-pyrite; (parentheses) indicate trace amounts.
[3] Sulfides divided into two types: O = sulfides taken from uranium mineralized rock (usually containing greater than 0.01 percent U_3O_8), and B = sulfides taken from barren rock.
[4] Geographic location of sulfide sample, mine from which collected, and cursory description of mineralogic and geologic occurrence of specimen as recorded on punched cards (7).

TABLE 1—*Continued*

Number[1]	Mineral[2]	Type[3]	Geologic Location[4]	S^{32}/S^{34}	δS^{34} ‰
			Sulfides from Triassic Sediments—*Continued*		
69	pyrite	B	Lucky Strike mine No. 2: pyrite nodule in barren sandstone.	23.02	−36.5
77	marcasite (pyrite)	B	Hidden Splendor mine: euhedral pyrite crystals occurring in green mudstone.	23.14	−41.9
80	pyrite	O	Hidden Splendor mine: sulfides in carbonaceous sandstone.	23.12	−41.0
81	pyrite	O	Hidden Splendor mine: sulfide rich stringer containing pyrite, sphalerite and abundant pitchblende, pink floom.	23.17	−40.8
82	pyrite	O	Hidden Splendor mine: large wood fragment impregnated with sulfides, pink bloom.	23.18	−43.7
83	pyrite	O	Hidden Splendor mine: sulfide with coalified wood.	23.10	−40.1
86	pyrite	O	AEC No. 8 mine, Temple Mountain: sulfide in mineralized sandstone associated with wood.	22.63	−18.9
88	pyrite	B	AEC No. 8 mine, Temple Mountain: sulfide in mudstone overlying thick conglomeritic bed, it is not associated with wood or mineralization but it overlies the ore horizon from which sample 86 was collected.	23.02	−36.5
89	pyrite-ferrosilite	O	AEC No. 8 mine, Temple Mountain: sulfide stringer about six inches long in coarse sandstone ore horizon, abundant cobalt bloom present, sandstone shows green stain—possibly copper.	22.80	−26.6
103	pyrite	B	AEC No. 8 mine, Temple Mountain: large pyritized log (2′×6′) in overlying barren mudstone.	23.04	−37.4
			White Canyon District, San Juan County, Utah		
106	pyrite	O	Happy Jack mine: disseminated pyrite.	23.24	−46.4
107	pyrite-marcasite	B	Happy Jack mine: pyrite nodule with wood.	22.92	−32.0
		O	Happy Jack mine: pyrite with wood in unoxidized ore.	23.32	−50.0
109	"chalcopyrite"	O	Happy Jack mine: chalcopyrite with ore position uncertain.	22.95	−33.3
110	chalcopyrite	O	Happy Jack mine: chalcopyrite impregnates coarse grained sandstone, collected in new drift to the west of old workings.	22.73	−23.4
111	chalcopyrite	O	Happy Jack mine: chalcopyrite in wood, collected in new drift.	22.97	−34.2
112	covellite-bornite	O	Happy Jack mine: rich seam of copper sulfides and uraninite.	23.12	−41.0
113	pyrite	B	Blue Lizard mine: pyrite with wood.	23.14	−41.9
114	pyrite	O	Blue Lizard mine: pyrite with wood.	23.24	−46.4
115	bornite (chalcopyrite)	O	Blue Lizard mine: bornite and chalcopyrite collected from high grade pitchblende boulder on dump.	no output	—
116	chalcopyrite	O	Blue Lizard mine: wood fragment replaced by chalcopyrite and pyrite. Some pitchblende with secondary urano sulfate minerals.	22.98	−34.7
117	chalcopyrite	O	Blue Lizard mine: chalcopyrite nodule.	22.91	−31.5
123	bornite (chalcopyrite)	O	Gismo mine: collected on dump but probably mined from bornite rich heading in new drift, in every case the bornite is associated with wood where it fills the shrinkage cracks.	22.94	−32.9
			Monticello District, San Juan County, Utah		
133	pyrite	B	MiVida mine: pyrite pseudomorph after carbonaceous matter in horizontal log, northeast side of drift.	23.14	−41.9

TABLE 1—*Continued*

Number[1]	Mineral[2]	Type[3]	Geologic Location[4]	S^{32}/S^{34}	δS^{34} ‰
			Sulfides from Triassic Sediments—*Continued*		
134	pyrite	O	MiVida mine: pyrite and pitchblende in horizontal coalified wood.	23.16	−42.8
136	pyrite	B	MiVida mine: pyrite crystal in barren coalified wood.	23.27	−47.7
137	pyrite	O	MiVida mine: associated with high grade ore, pitchblende in wood with pyrite.	23.19	−44.1
138	pyrite	O	MiVida mine: little pyrite associated with abundant greenockite and high grade pitchblende.	no output	—
139	pyrite	O	MiVida mine: little pyrite associated with greenockite and high grade pitchblende.	no output	—
			Monument Valley District, Apache County, Arizona		
144	pyrite	B	Monument No. 2 mine: collected in south extension of mine in Shinarump formation, occurs in nodules and lenses about one inch in diameter.	22.86	−29.3
145	pyrite	O	Monument No. 2 mine: pyrite associated with pitchblende, doloresite, sulfur (native) in blue-black ore pod, carbonaceous material present.	22.75	−24.3
146	pyrite	B	Monument No. 2 mine: collected from North workings in sulfide impregnated sandstone.	23.20	−44.6
			Sulfides from Tertiary Sediments		
			Wind River Formation (Eocene)		
			Gas Hills District, Fremont County, Wyoming		
179	pyrite-marcasite	B	Lucky Mc mine: disseminated pyrite collected from silty sandstone bed about six inches thick.	23.28	−48.2
182	marcasite (pyrite)	B	Lucky Mc mine: abundant sulfide collected from core of solid gray sandstone drilled in bottom of pit.	23.01	−36.0
183	marcasite-pyrite	B	Lucky Mc mine: collected from drill core in coarse arkosic sandstone.	22.92	−32.0
184	pyrite	O	Lucky Mc mine: collected from dark high grade coarse sandstone that contains streaks of yellow and green secondary uranium minerals.	22.85	−28.8
			Miscellaneous Samples		
			Espinazo Volcanics (Oligocene)		
1AB-41-57 I. Breger	marcasite	O	Santa Fe County, New Mexico La Bajada mine: massive sulfides and dispersed organic, resinous appearing material.	23.03	−37.0
			Morrison Formation		
AW-138-53	native sulfur	B	Gypsum Valley District, San Miguel County, Colorado Pitchfork mine: Sulfur occurs on joint surfaces and in small veinlets in highly fractured sandstone near axis of anticline of Salt Wash member that rests directly upon Paradox member of the Hermosa formation. Sulfur may, therefore, have been derived from the cap rock of salt plug in the underlying Paradox member.	22.28	− 3.2

TABLE 1—*Continued*

Number[1]	Mineral[2]	Type[3]	Geologic Location[4]	S^{32}/S^{34}	δS^{34} ‰
			Miscellaneous Samples—*Continued*		
I. Breger (NA-1)	pyrite	O (7.51% U_3O_8)	San Rafael District, Emery County, Utah Vanadium King No. 7 mine: hand-picked and hand-cleaned sample from coalified log which contains *organic sulfur* and *pyrite*. (The chemical procedure of separating the organic sulfur in order to determine its isotopic composition, has not yet been done.)	23.01	−36.0
			Wind River Formation (Eocene)		
(R. Garrels) 244-RGC-55	pyrite		Gas Hills District, Fremont County, Wyo. Sarcophagus Butte. (No information on geologic occurrence.)	21.69	+23.4
			Morrison Formation		
(R. Garrels) 96-RGC-55A	chalcocite		Slick Rock District, San Miguel County, Colorado Cougar mine. (No information on geologic occurrence.)	22.92	−32.0
(R. Garrels) 102-RGC-550	chalcocite		Cougar mine. (No information on geologic occurrence.)	22.99	−35.1
			Entrada Formation		
(R. Garrels) 74-RGC-550	galena		Rifle District, Garfield County, Colorado Rifle mine. (No information on geologic occurrence.)	22.25	− 2.2
			Sulfides in Magmatic Hydrothermal Uranium Deposits		
F. W. Christiansen	pyrite		Marysvale District, Piute County, Utah V.C.A. Bullion Monarch property, No. 2 Vein, 700 level. Pyrite disseminated in granodiorite.	22.31	− 4.5

the same sample number used by Coleman and Delevaux (5) in their selenium study. The miscellaneous samples are listed by the names of the persons from whom the samples were obtained.

Following the name of the mining district and mine from which the samples were collected, a brief description is given of the geologic and mineralogic occurrence of each specimen, information that was obtained from the respective punched-cards (7) upon which data pertaining to each sample had been recorded by the collector. Table 1 also indicates the mineral species and the "type" of sulfide; i.e., O = sulfides taken from mineralized rock (generally showing > 0.01 percent U_3O_8), and B = sulfides taken from barren rock.

In order to provide a rapid comparison of these ratios to sedimentary sulfide ratios and to the presently known range (based on 14 samples) of S^{32}/S^{34} analyses (6, 23) of naturally occurring hydrogen sulfide of organic origin, a graphical representation is given by Figure 1. The height of the short line at a given ratio value is proportional to the number of samples that have the same value. In indicating the values of the sedimentary sulfides, the recent ratios reported by Vinogradov et al. (27) are indicated separately by lines located below the previously published sedimentary sulfide ratios

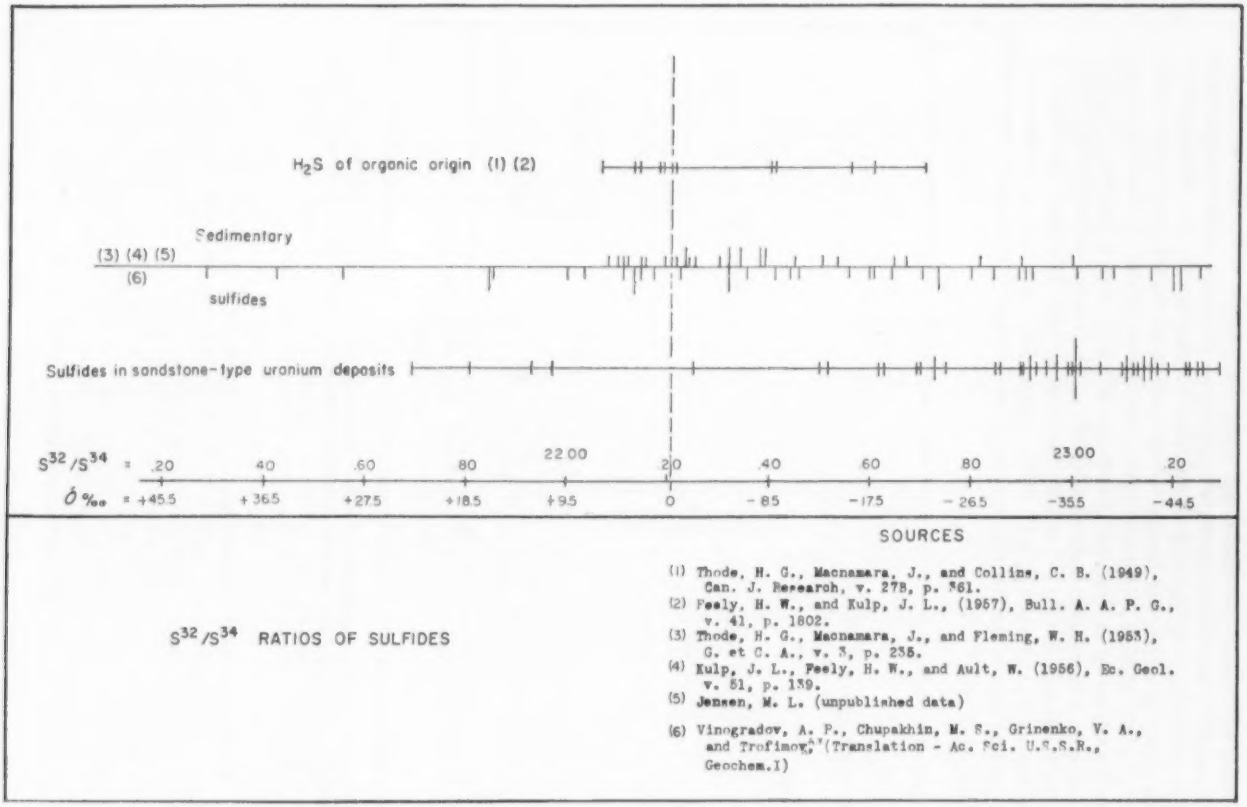

H2S of organic origin (1) (2)
Sedimentary
(3) (4) (5)
(6)
sulfides
Sulfides in sandstone-type uranium deposits
S32/S34 = .20 .40 .60 .80 22.00 .20 .40 .60 .80 23.00 .20
δ ‰ = +45.5 +36.5 +27.5 +18.5 +9.5 0 -8.5 -17.5 -26.5 -35.5 -44.5
S32/S34 RATIOS OF SULFIDES
SOURCES
(1) Thode, H. G., Macnamara, J., and Collins, C. B. (1949), Can. J. Research, v. 27B, p. 361.
(2) Feely, H. W., and Kulp, J. L., (1957), Bull. A. A. P. G., v. 41, p. 1802.
(3) Thode, H. G., Macnamara, J., and Fleming, W. H. (1953), G. et C. A., v. 3, p. 235.
(4) Kulp, J. L., Feely, H. W., and Ault, W. (1956), Ec. Geol. v. 51, p. 139.
(5) Jensen, M. L. (unpublished data)
(6) Vinogradov, A. P., Chupakhin, M. S., Grinenko, V. A., and Trofimov, V. (Translation - Ac. Sci. U.S.S.R., Geochem.I)

FIG. 1. The spread of S^{32}/S^{34} ratio values and permil values for natural hydrogen sulfide of organic origin, sedimentary sulfides, and sulfides associated with sandstone-type uranium deposits. Height of line indicating ratio value is proportional to the number of specimens having the same ratio.

reported by Thode (24) and Kulp, Ault, and Feely (14). This was done, not because of any doubt about the accuracy or precision of the Russian ratio results or because of the lack of the same troilite sample as a standard for comparison of ratios, but because of the abortively brief geological and mineralogical description of each of the 41 widely geographically scattered samples. The importance of an adequate description of the geological and mineralogical occurrence of specimens upon which isotopic studies are performed has been stressed repetitively (11). It may be possible that a sample described as "pyrite in clay, Kirov district" (from translation) did have a sedimentary origin, but with no further information given it might just as easily have had a hydrothermal origin.

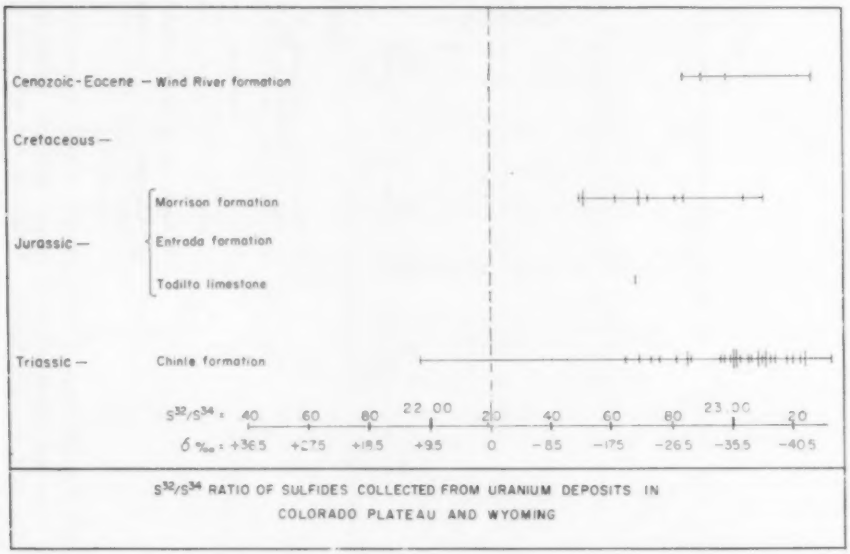

Cenozoic-Eocene — Wind River formation
Cretaceous —
Morrison formation
Jurassic — Entrada formation
Todilto limestone
Triassic — Chinle formation
S32/S34 = 40 60 80 22.00 20 40 60 80 23.00 20
δ ‰ = +36.5 +27.5 +18.5 +9.5 0 −8.5 −17.5 −26.5 −35.5 −40.5
S32/S34 RATIO OF SULFIDES COLLECTED FROM URANIUM DEPOSITS IN COLORADO PLATEAU AND WYOMING

FIG. 2. The spread of S^{32}/S^{34} ratio values and permil values of sulfides collected from sandstone-type uranium deposits listed according to the stratigraphic horizons from which the samples were collected. Height of line indicating ratio value is proportional to the number of specimens having the same ratio.

Similar graphical representations are given by Figures 2 and 3. The former indicates the ratio values of the sulfides associated with uranium deposits separated according to the stratigraphic horizon from which the samples were collected. The latter shows the spread in ratio values of those samples of which two or more were collected from the same deposit. The ratios are separated according to mine occurrence and the ratios are indicated as "O" (sulfide associated with Uranium mineralization $> 0.01\%$ U_3O_8) or "X" (sulfide occurring in uranium barren rock).

The miscellaneous samples include a heterogeneous but significant group of specimens that were contributed by several persons. One of these samples, obtained from Alice Weeks, is native sulfur that was collected from the Morrison formation, although the sulfur was derived, it is believed by some, from the cap rock of the salt plug from the underlying Paradox member. It may be more reasonable to suggest that it was formed by the following reaction: $UO_2^{++} + H_2S \rightarrow UO_2 + S + 2H^+$. Sample N2–1, collected and studied by Irving M. Breger, contains organic native sulfur (2), which has not yet been

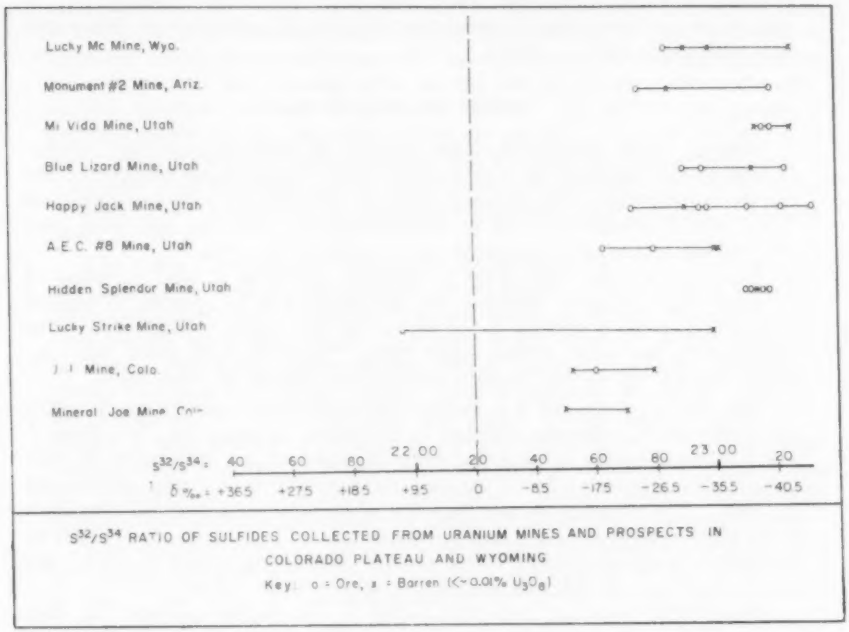

Lucky Mc Mine, Wyo.
Monument #2 Mine, Ariz.
Mi Vida Mine, Utah
Blue Lizard Mine, Utah
Happy Jack Mine, Utah
A.E.C. #8 Mine, Utah
Hidden Splendor Mine, Utah
Lucky Strike Mine, Utah
J. J. Mine, Colo.
Mineral Joe Mine, Colo.
S32/S34 : 40 60 80 22.00 20 40 60 80 23.00 20
δ ‰ : +36.5 +27.5 +18.5 +9.5 0 -8.5 -17.5 -26.5 -35.5 -40.5
S32/S34 RATIO OF SULFIDES COLLECTED FROM URANIUM MINES AND PROSPECTS IN COLORADO PLATEAU AND WYOMING
Key: o = Ore, x = Barren (<~0.01% U3O8)

FIG. 3. S^{32}/S^{34} ratio values and permil values of sulfides collected from uranium deposits of the Colorado Plateau and Wyoming. O = Ore, X = Barren ($<\sim 0.01\%$ U_3O_8).

removed (by chemical means) from the sample although the ratio of the pyrite of the specimen is reported. The origin of the organic sulfur is not known definitely although it is believed to be non-mineral in nature. It is interesting to note, however, that the organic sulfur content is high in high-uranium content coalified wood but is low or "normal" in those containing less than 1 percent uranium. This relationship, determined by Irving M. Breger (3), is interpreted by him "to indicate that sulfur in some form (H_2S?) entered with the mineralizing fluid and, under conditions of min-

eralization, interacted with the coal to produce organic sulfur constituent groups."

Unfortunately, only one specimen of generally undoubted magmatic hydrothermal origin is included, a specimen from the Marysvale district, Utah. Attempts are being made, however, to obtain some sulfides from the intrusive rocks of the Colorado Plateau. The sample collected from the Marysvale district, which is located on the western edge of the Colorado Plateau, has a ratio of 22.31 which, interestingly enough, is within the range of sulfur ratios obtained for many of the base-metal sulfide deposits of the Basin-Range province, although admittedly one sample is of little if any significance. It will not be too surprising, however, to find that all sulfides from Marysvale have ratios near 22.3

DISCUSSION OF RESULTS

General.—The application of the specialty of stable isotopic ratio investigations to the study of the origin of mineral deposits is no panacea to the problems confronting the economic geologist, but instead is merely one more "tool" that is available to aid in determining the processes that have been effective in concentrating materials in the crust of the earth.

No claim is made that these 57 samples represent a valid sampling of sandstone-type uranium deposits, but nevertheless it is possible to present certain hypotheses pertaining to the genesis of these deposits based upon ideas suggested by the results of this initial study. It is hoped, however, that continued studies will provide further tests for the validity of these ideas.

Discussion.—Although it is evident that most of the samples analyzed for this study are significantly enriched in the lighter isotopes, i.e., S^{32}, Table 1 and Figures 2 and 3 indicate that there is, however, no correlation of ratio values with different mineral species, stratigraphic host rocks, or mineral deposits. The presence or non-presence of carbonaceous material, variation in the abundance of selenium, and the occurrence with uranium mineralization, in contrast to occurrences in barren ground (containing $< 0.01\%$ U_3O_8) are factors that have no apparent relationship to the sulfur ratios.

The S^{32}/S^{34} ratio of meteoritic sulfur is remarkably uniform but does vary from about 22.18 to 22.24 (1, 16); terrestrial sulfur is presumably similar, although it may differ slightly from meteoric sulfur (which is derived supposedly from the band of the asteroids) if there had been some fractionation of isotopes in the "dust cloud" that provided the material for the formation of the planets by accretion during the formation of the solar system. Ault (1), for example, has suggested that primordial earth sulfur had a ratio of about 22.14, although this very interesting but statistical conclusion is based upon rather tenuous assumptions. Nevertheless, the ratios of sulfides associated with sandstone-type uranium deposits are notably lighter than either meteoritic or primordial terrestrial sulfur. These high ratios are, however, the outstanding feature of the study, and they are immediately suggestive, but certainly not diagnostic, of sulfur derived from hydrogen-sulfide of organic origin.

On the other hand the relatively broad spread in high ratios of sulfides from the same deposit, especially contiguous samples formed contemporaneously, is much more diagnostic of a sulfur source derived from hydrogen sulfide of organic origin. This reasoning is based both upon the spread in ratios of first, spatially closely related organic hydrogen sulfide samples and, second, upon juxtaposed sedimentary sulfides formed, it is believed, through hydrogen sulfide reacting with iron sulfate resulting in the precipitation of iron sulfide and the release of the heavy sulfur sulfate ion to the sea.

Although the processes by which sedimentary sulfides form are not fully understood and are in need of further study, sulfur isotopic ratio studies have provided some information pertaining to these processes. The presence of hydrogen sulfide generated by anerobic bacteria in organic-bearing muds does seem to provide the reducing environment that could bring about the conversion of soluble sulfates to insoluble sulfides. As sulfates are generally enriched in S^{34}, and sedimentary sulfides are commonly enriched in S^{32}, as is also hydrogen sulfide, it seems apparent that the sulfur in sedimentary sulfides is derived from hydrogen sulfide, whereas sea-water sulfates derived from the released anion of the soluble sulfates are relatively heavy, having a ratio of about 21.76 (6).

The ratios of sedimentary sulfides as indicated by Figure 1, do corroborate the above hypothesis in that the samples are generally enriched in S^{32}. This relationship was more evident prior to the results of Vinogradov et al. (27), even though these samples also give an average ratio above the meteoritic standard. Admittedly, however, even though the specimens studied by Vinogradov that bear low ratios are rare, there is certainly no reason why these heavy sedimentary sulfides should not exist. Rather heavy sulfate, even though it does undergo fractionation during reduction, may produce sulfur comparatively enriched in S^{32} but still be relatively rich in S^{34}, although less so. The probability, however, of sedimentary sulfides having low ratios is certainly less than the probability of sedimentary sulfides having high ratios.

Convincing evidence of the fully expected fact that some anerobic bacteria are capable of utilizing the oxygen in sulfates through the reduction of sulfate to sulfide, resulting in the enrichment of S^{32} in the sulfide, has been well demonstrated by experiments performed by Thode et al. (17, 22, 25) and Feely and Kulp (6).

As the enrichment of S^{32} in the sulfides associated with uranium deposits is high, in fact extremely high, data on the efficacy of fractionation of sulfates by anerobic bacteria must be considered. Experiments (6, 22) in which cultures of these bacteria have been grown under controlled conditions in the presence of sulfate and of course organic matter (as a food source), have resulted in the production of hydrogen sulfide that has been enriched in the lighter isotope to the maximum extent of 2.7 percent, this at a temperature of 14° C. The majority of the experiments, however, resulted in an enrichment of S^{32} in the sulfide of between 1.0 to 1.5 percent. In contrast, however, analyses of natural samples by Thode et al. (25) from Cyrenaica, North Africa, infer an isotopic enrichment of about 3.2 percent. They also reported

a possible enrichment as great as 4.5 percent of hydrogen sulfide over associated sulfate from well water in Ontario.

Theoretically, however, even greater fractionation can take place. The partition function ratios for sulfate and hydrogen sulfide are as follows according to Szabo et al. (21) and Tudge and Thode (26):

$$\frac{Q S^{34}O_4^{=}}{Q S^{32}O_4^{=}} = 1.088 \text{ at } 25^\circ \text{ C}$$

and

$$\frac{Q H_2S^{34}}{Q H_2S^{32}} = 1.013 \text{ at } 25^\circ \text{ C},$$

where Q represents the respective partition functions of the specific isotopic compound indicated. In the reduction of sulfate to hydrogen sulfide by the exchange reaction given below:

$$S^{32}O_4^{=} + H_2S^{34} \rightleftarrows S^{34}O_4^{=} + H_2S^{32}$$

the equilibrium constant is:

$$K = \frac{1.088}{1.013} = 1.074 \text{ at } 25^\circ \text{ C}.$$

A fractionation, therefore, as great as 7.4 percent is theoretically possible. Under a unidirectional process, which may be more likely during the slow migration of sulfate waters through permeable channels and past organic matter containing sulfate reducing anerobic bacteria, the fractionation may even approach 8.8 percent.

At temperatures above 25° C, the fractionation will decrease. Sakai (20) has computed the partition functions of various sulfur compounds at temperatures of 25, 50, 100, 500, and 1,000° C. With this information a graph of the fractionation factors versus temperature for $H_2S/SO_4^{=}$ is given by Figure 4, which indicates the decrease in the fractionation factor with increased temperature.[2] The fractionation by anerobic bacteria is limited, of course, to temperatures below 100° C. The temperature factor is discussed in a following portion of this paper.

These large fractionation factors strengthen the suggested origin of the high ratios reported in this paper. The establishment of this large fractionation extent is important, especially because many of the ratios given in this paper are not only the highest yet obtained for sulfur-bearing material (Specimen 108 with a ratio of 23.32 is the highest S^{32}/S^{34} ratio measured for a mineral), but also because some of the closely associated sulfides that have been analyzed during this study have significantly lower ratios. For example, specimen 86 collected from the A.E.C. No. 8 Mine has a ratio of 22.63, whereas specimen 87, which "overlies the ore horizon from which sample 86 was collected" has a ratio of 23.02. This is a percentage variation of about

[2] The partition function ratios at 25° C computed by Sakai (20) differ slightly from those computed by Tudge and Thode (26).

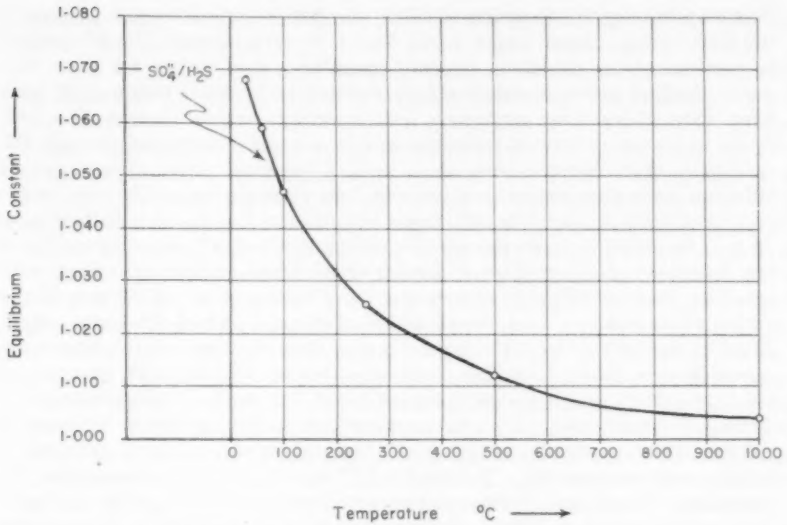


FIG. 4. Value of equilibrium constant versus temperature for the isotopic exchange reaction: $S^{32}O_4^= + H_2S^{34} \rightleftarrows S^{34}O_4^= + H_2S^{32}$ (after Sakai).

1.7 percent, which is quite reasonable, but the sample of lower ratio was presumably derived from sulfate of an even lower ratio; assuming that it was as low as 21.82 (the lowest ratio obtained from a Colorado Plateau sulfide), the percentage variation between this and the higher ratio of 23.02 is about 5.5 percent, still considerably below the theoretical values obtained by Szabo (21), but considerably above the maximum experimental value of 2.7 percent reported by Feely (6).

It should be realized that the fractionation of the isotopes is the result of the isotopic reaction of the reduction of the sulfate to hydrogen sulfide. Any mechanism that can cause this reduction under equilibrium conditions will result in the same degree of fractionation. Sulfate-reducing bacteria are merely one natural agency by which this reduction occurs. It is evident from presently known sulfur isotopic studies and the computed fractionation factors, furthermore, that the process of reduction of sulfate to sulfide by anerobic bacteria does not take place under even approaching equilibrium conditions.

The food or energy source of *Desulfovibrio,* by which generic name all sulfate-reducing bacteria are known, consists of organic compounds.[3] These bacteria can be expected, therefore, in almost any environment containing organic matter and sulfate solutions, e.g., soil, swamps, water-wells, oil-field waters, salt-domes, both mud and sand in sea-bottoms, and so forth.

It is not unreasonable, therefore, to assume that sulfate-reducing bacteria became incorporated in, for example, the Salt Wash member of the Morrison

[3] Elemental hydrogen evidently can be utilized by some species.

formation during the deposition of this member. Organic matter present in the form of logs, stems, twigs, roots, leaves, or carbonaceous "trash" pockets in portions of the sandstone channels provided a food supply for these bacteria. Sulfate waters of either or both meteoric and connate origin could have been reduced by these organisms and hydrogen sulfide thereby liberated. Some of the early formed hydrogen sulfide may have migrated through the sandstone short distances into shale or clay horizons which, if iron sulfate solutions were then encountered, provided the reducing agency for the formation of sulfides (where, in fact, some sulfides are found) at a rather early stage. Incidentally, even though this indicates a lack of contemporaneity in the formation of the sulfides in barren rock versus sulfides associated with uranium, there is still little reason why there should be any difference in the ratios of the samples in as much as all of the sulfur had the same origin. Much of the hydrogen sulfide, however, may have remained until a later time, approximately 60 to 75 million years ago, before reacting with uraniferous solutions, which possibly were squeezed out of the overlying volcanic-ash-rich Brushy Basin member (29) into the more porous and permeable channels of the Salt Wash member, through which they migrated until hydrogen sulfide locales were encountered. The soluble U^{+6} ion would then be reduced to the insoluble U^{+4} ion, and ferrous sulfate solutions would react with hydrogen sulfide to form iron sulfides. If the solutions were unusually rich in copper sulfate, admittedly not a common condition but certainly quite possible, copper sulfides would naturally be concentrated by the hydrogen sulfide (*a la* Happy Jack deposit) and these copper sulfides would exhibit the typically high ratios comparable to iron sulfides of the province as for the Happy Jack deposit they, of course, do. It is somewhat of an enigma why many economic geologists assert that dense, massive, and crystalline sulfides have formed from magmatic hydrothermal solutions when these same persons are quite aware of sedimentary sulfides having the same features.

Although it is well known that lignitic, woody, or carbonaceous material is effective in concentrating uranium (8), the presence of uranium in an area where there is a lack of carbonaceous material is not easily explained. It might, however, be explained by the presence of hydrogen sulfide that had migrated from the locale of the organic food supply needed by the anerobic bacteria, to an organic barren zone. In so doing, it thereby provided the reducing environment for the concentration of a uraniferous deposit, even though there may now be no evidence of the cause of the reducing environment as the hydrogen sulfide is no longer present.

An example where the hydrogen sulfide *is now* present is offered by the numerous occurrences of uranium oxide deposits in the Wind River formation, Gas Hills district, Wyoming, where uranium mineralization is not generally accompanied by plant carbonaceous material; in fact, the material is mostly missing in much of the best ore.

Gas seeps, however, are prevalent in the area from which hydrogen sulfide is escaping into the atmosphere. It is believed that at the north end of the Gas Hills anticline, where several seeps are present, the gas is derived from

the underlying Frontier formation, which is known to be a reservoir rock for oil and gas in this area.

It is interesting, therefore, to quote from an excellent study of this area by Eugene Grutt (10), wherein he suggests that "under the conditions occurring in the Gas Hills area, evidence suggests that hydrogen sulfide may be mainly responsible for the formation of important uranium deposits, because plant carbonaceous material is not abundant, and even when present it is not always mineralized even though in or near uraninite ore deposits" (10, p. 5). Four iron sulfide samples (nos. 179, 182, 183, and 184) from the Lucky Mc mine, Gas Hills district, were isotopically analyzed and have "typical" (for this study) S^{32}/S^{34} ratios varying between 22.85 to 23.28, which if I may be permitted to be redundant, are remarkably high in ratio, spread over a broad range, and are therefore quite suggestive of sulfur derived from hydrogen sulfide of organic origin. It will be interesting to determine the S^{32}/S^{34} ratio of not only the hydrogen sulfide gas from these seeps but the abundant finely-divided ferrous sulfide that forms below the water surface in the seeps by a reaction between ferrous sulfate and hydrogen sulfide, which as I have already suggested is probably the same reaction that has formed most of the sedimentary sulfides and the sulfides associated with sandstone-type uranium deposits. The analyses will be even more interesting if ratios can be obtained from the sulfate that should also be present in the water.

Grutt, of course, for excellent reasons, postulates a petroleum origin for the hydrogen sulfide gas. Because of the widespread occurrence of some uranium throughout almost all of the plateau area, even though petroleum is much more prevalent in portions of the Colorado Plateau than previously realized (the Aneth region, for example), it is still much more reasonable to infer that the food for the bacteria was not petroleum but was, instead, the almost ubiquitous plant carbonaceous [4] matter that is present in these beds.

As the Gas Hills deposits may be of relatively recent origin, maybe even Pleistocene, it is significant that hydrogen sulfide is present at this opportune time.

In contrast, the deposits of the Colorado Plateau were formed from 60 to 75 million years ago in sediments of camparable to almost three times these ages. It seems reasonable, however, to believe that anerobic bacteria began to produce hydrogen sulfide as early as during diagenesis of the sediments. With continual burial and covering of the sediments, the environmental conditions of temperature and pressure gradually increased.

As well as can be determined, pressure seems to have little bearing on the environmental conditions in which anerobic bacteria have been found to occur. Survival of bacteria at pressures of 6,000 atmospheres has been shown (15). Zobell and Anderson (30) report that these organisms occur at depths of 2,000 meters of water, and Carey and Wakeman (4) have recovered bacteria from sea muds at depths as great as 5,000 meters with no effect on the organisms, indicating that neither this great hydrostatic pressure nor its release,

[4] Hydrogen sulfide is created in abundance during the compaction and conversion of plant material to peat, lignite, and coal, but even considering the abundance of coal in the plateau, it is still much more limited both stratigraphically and areally than is uranium.

by bringing them to the surface, affects the viability of the bacteria. Finally, Zobell (32) has reported the recovery of bacteria from samples collected in the Philippine Trench from depths greater than 10,000 meters. Furthermore, these barophilic bacteria thrive better during incubation periods at 1000 atmospheres than at 1 atmosphere.

Increased temperatures, however, are a different matter but data on this factor are sparse. Zobell et al. (31) have found that some hydrocarbon oxidizing bacteria are active at temperatures as low as 0° C, and others thrive better at 55° C than at 20° C, although most marine bacteria do prefer temperatures between 0 to 4° C. Zobell does suggest, however, that "there must be other places in nature to find hydrocarbon oxidizing bacteria which tolerate higher temperatures than those which occur in the sea," and he refers to a paper (19) in which aerobic bacteria are reported to be widely distributed in environments having temperatures ranging from 45 to 85° C.

Assuming an average geothermal gradient of about 30° C/km for the Mesozoic sediments of the Plateau during early Cenozoic time, the temperature of formation of some of the sandstone-type uranium deposits, covered by about 10,000 feet of overburden, must have been in excess of 100° C. It is doubtful that anerobic bacteria could exist at this temperature. Before this condition was reached, however, it is certainly possible that hydrogen sulfide had been produced in some abundance throughout a long period of time. Incidentally, hydrothermal connate solutions at this temperature should be capable of producing evidence of hydrothermal alteration especially in arkosic sandstones. I cannot agree, therefore, that wall rock alteration associated with some sandstone-type uranium deposits is proof of a magmatic hydrothermal origin as claimed by some investigators.

As the period of mineralization is subsequent to the formation of hydrogen sulfide, the possible escape of the gas from the sediments before mineralization should be considered, even though there is no more difficulty in retaining the hydrogen sulfide gas within these strata than in retaining hydrocarbon gases within reservoir rocks in suitable oil-traps. Sour crude oil, of course, contains hydrogen sulfide which has not escaped, even though the oil producer may prefer that it had.

As further evidence in partial support of the thesis of this paper, the reader should be reminded that Gruner (9) has demonstrated the efficacy of hydrogen sulfide as a reducing agent in precipitating uraninite from a uranium solution. Miller (18) has reported similar results. Grutt (10), furthermore, reports that "the precipitation of uranium as uraninite from solutions by the reducing action of hydrogen sulfide was verified" by the Colorado School of Mines Research Foundation. It might, parenthetically, also be noted that this Foundation not only determined "that the presence of ferrous ion was a definite factor aiding precipitation, but experiments using the naturally-formed, finely-divided ferrous sulfide collected from the Gas Hills seeps demonstrated that ferrous sulfide alone in an inert atmosphere could not precipitate uranium from solution. They also determined that natural gas with hydrogen sulfide removed had very little effect in precipitating uranium from solution."

The establishment, therefore, of hydrogen sulfide as an effective reducing agent, capable of precipitating uraninite from uranium solutions, is apparently well established.

I am indebted to R. M. Garrels for suggesting the possibility of a more effective reducing agent, viz., hydrogen which might be provided by hydrogen sulfide and ferric oxide reacting as follows:

$$4H_2S + Fe_2O_3 \rightarrow 2FeS_2 + H_2 + 3H_2O$$

Note that this reaction also explains the lack of the characteristic reddish color of the sediments associated with sandstone-type uranium deposits, as the cause of this color, ferric oxide, is reduced to ferrous sulfide.

CONCLUSIONS

No attempt is being made to claim the omnipotent importance of hydrogen sulfide or organic origin as the sole precipitating agency that resulted in the formation of the thousands of sandstone-type uranium deposits of the Colorado Plateau. At the same time, however, it is possible that the effectiveness of the role of this agent may not be as well accepted nor appreciated as is warranted. It is hoped, however, that the results and discussion of this isotopic study have provided evidence for hydrogen sulfide in forming some, if not many, of these sandstone-type uranium deposits.

LABORATORY OF ECONOMIC GEOLOGY,
YALE UNIVERSITY,
NEW HAVEN, CONN.,
Mar. 15, 1958

REFERENCES

1. Ault, W. V., 1957, Geochemical processes and sulfur-isotope fractionation: [Abstract] Bull. Geol. Soc. America, v. 68, p. 1697.
2. Breger, I., Oct. 15, 1957, Written communication.
3. ——, June 4, 1957, Written communication.
4. Carey, C. L., and Waksman, S. A., 1934, The presence of nitrifying bacteria in deep seas: Science, v. 79, p. 349–350.
5. Coleman, R. G., and Delevaux, M., 1957, Occurrence of selenium in sulfides from some sedimentary rocks of the western United States: ECON. GEOLOGY, v. 52, p. 499–527.
6. Feely, H. W., and Kulp, J. L., 1957, Origin of Gulf Coast salt-dome sulfur deposits: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 1802–1853.
7. Finch, W. I., 1957, Application of punched cards to geologic data concerning uranium deposits in sandstone: ECON. GEOLOGY, v. 52, p. 180–191.
8. Garrels, R. M., 1957, Geochemistry of "Sandstone-type" uranium deposits: 2nd Nuclear Engineering and Science Conference, Paper No. 57-NESC-121, p. 1–6.
9. Gruner, J. W., 1952, New data of synthesis of uranium minerals: AEC Annual Report, RNO-983, Part I.
10. Grutt, E., 1957, Environment of some Wyoming uranium deposits: 2nd Nuclear Engineering and Science Conference, Paper No. 57-NESC-69, p. 1–12.
11. Jensen, M. L., 1957, Sulfur isotopes and mineral paragenesis: ECON. GEOLOGY, v. 52, p. 269–281.
12. ——, 1957 [Abstract], The Significance of S^{32}/S^{34} ratios on the origing of sulfides in uranium deposits of the Colorado Plateau: Geol. Soc. America Bull., v. 68, p. 1752.
13. Kerr, P. F., 1950, Mineralogic studies of uraninite and uraninite-bearing deposits: Interim Tech. Report, U. S. Atomic Energy Com., Div. of Raw Materials.
14. Kulp, J. L., Ault, W. V., and Feely, H. W., 1956, Sulfur isotope abundances in sulfide minerals: ECON. GEOLOGY, v. 51, p. 139–149.

15. Larsen, W. P., Hartzell, T. B., and Diehl, H. S., 1918, The effects of high pressures on bacteria: Jour. Infect. Dis., v. 22, p. 271–279.
16. Macnamara, J., and Thode, H. G., 1950, Comparison of the isotopic constitution of terrestrial and meteoritic sulfur: Phys. Rev., v. 78, p. 307.
17. ——, and Thode, H. G., 1951, The distribution of S^{34} in nature and the origin of native sulfur deposits: Research (London), v. 4, p. 582.
18. Miller, L. J., 1955, The chemical environment of pitchblende: AEC Annual Report, RME-3110, Part I.
19. Morrison, L. E., and Tanner, F. W., 1922, Studies on thermopilic bacteria. I. Aerobic thermophilic bacteria from water: Jour. Bact., v. 7, p. 343–366.
20. Sakai, H., 1957, Fractionation of sulfur isotopes in nature: Geochim. et Cosmochim. Acta, v. 12, p. 150–169.
21. Szabo, A., Tudge, A., Macnamara, J., and Thode, H. G., 1950, Distribution of S^{34} in nature and the sulfur cycle: Science, v. 111, p. 464.
22. Thode, H. G., Kleerskoper, H., and McElcheran, D., 1951, Isotope fractionation in the bacterial reduction of sulfate: Research (London), v. 4, p. 581–582.
23. ——, Macnamara, J., and Collins, C. B., 1949, Natural variations in the isotopic composition of sulfur and their significance: Can. J. Research, v. 27B, p. 361–373.
24. ——, —— and Fleming, W. H., 1953, Sulfur isotope fractionation in nature and geological and biological time scales: Geochim. et Cosmochim. Acta, v. 3, p. 235–243.
25. ——, Wanless, R. K., and Wallouch, R., 1954, The origin of native sulfur deposits from isotope fractionation studies: Geochim. et Cosmochim. Acta, v. 5, p. 286–298.
26. Tudge, A. P., and Thode, W. G., 1950, Thermodynamic properties of isotopic compounds of sulfur: Can. J. Research, v. 28B, p. 567–578.
27. Vinogradov, A. P., 1956, S^{32}/S^{34} isotopic composition of meteorites and of the earth: International conference on radioisotopes in scientific research, UNESCO/NS/RIC/82.
28. ——, Chupakhin, M. S., Grinenko, V. A., and Trofimov, A. V., 1956, The ages of sedimentary pyrites and the isotopic composition of sulfur, Geokhimiia 1, Translation from Geol. Survey of Canada, Library Cat. No. 8A162.
29. Waters, A. C., and Granger, H. C., 1953, Volcanic debris in uraniferous sandstones, and its possible bearing on the origin and precipitation of uranium: U. S. Geol. Survey Circular 224, p. 1–26.
30. Zobell, C. E., and Anderson, D. Q., 1936, Vertical distribution of bacteria in marine sediments: Am. Assoc. Petroleum Geologists Bull., v. 20, p. 258–269.
31. ——, Grant, C. W., and Haas, H. F., 1943, Marine microörganisms which oxidize petroleum hydrocarbons: Am. Assoc. Petroleum Geologists Bull., v. 27, p. 1175–1193.
32. ——, 1953, Bacterial life at the bottom of the Philippine Trench: Science, v. 115, p. 507–508.

Economic Geology
Vol. 53, 1958, pp. 617-619

SCIENTIFIC COMMUNICATIONS

SOLUBILITY PRODUCT AND ORE PRECIPITATION

In considering the application of the solubility product to problems of ore genesis Verhoogen (1949) assumed two salts CA and KB with solubility products $(SP_1)_{ca}$ and $(SP_1)_{kb}$, respectively, at temperature T_1, and $(SP_2)_{ca}$ and $(SP_2)_{kb}$ at the temperature T_2.

By the application of solubility product principles if CA precipitates at T_1 and KB does not precipitate then,

$$(C)(A) \geqq (SP_1)_{ca}$$

and

$$(K)(B) < (SP_1)_{kb}$$

or

$$\frac{(C)(A)}{(K)(B)} > \frac{(SP_1)_{ca}}{(SP_1)_{kb}}, \tag{1}$$

where (C) etc. is the concentration of C etc.

Further, if at the higher temperature T_2 the solution is just saturated with both CA and KB, then

$$\frac{[C][A]}{[K][B]} = \frac{(SP_2)_{ca}}{(SP_2)_{kb}}, \tag{2}$$

where [C] etc. is the concentration of C etc. at T_2.

Verhoogen then assumed that $(C)(A)/(K)(B) = [C][A]/[K][B]$ and substituting into (1) obtained

$$\frac{(SP_2)_{ca}}{(SP_2)_{kb}} > \frac{(SP_1)_{ca}}{(SP_1)_{kb}}. \tag{3}$$

He pointed out that if (3) is satisfied then CA will precipitate alone at T_1, if not then KB precipitates alone or neither precipitates. CA and KB precipitate together if

$$(C)(A) > (SP_2)_{ca}/(SP_2)_{kb} \cdot (K)(B).$$

Verhoogen's analysis thus indicates that it is the ratio of the SP's rather than their absolute values that determines the order of precipitation, so that if the ratio of the SP's at T_2 is greater than at T_1, then CA will precipitate at T_1 even though it might have the larger SP He shows that for

the particular case of ZnS and PbS,

$$\frac{(SP_{400})_{ZnS}}{(SP_{400})_{PbS}} = 8.7 \cdot 10^5 \qquad \frac{(SP_{100})_{ZnS}}{(SP_{100})_{PbS}} = 0.4 \cdot 10^5$$

and suggests that ZnS would precipitate alone at 100° C from a solution that had been saturated with both salts at 400° C.

It is an observed fact that ZnS does precipitate before PbS in hydrothermal deposits in spite of its greater solubility. Nevertheless free energy considerations would preclude the substance with the higher solubility product precipitating first. A closer examination of Verhoogen's treatment reveals the following. In substituting (2) into (1) he has assumed that (C)(A) = [C][A] and (K)(B) = [K][B]. In fact, if (C)(A) just equals (or slightly exceeds) the SP at T_1 then it can only also equal it at T_2 if the solubility of the salt does not vary between T_1 and T_2. Also, if (K)(B) < SP at T for it to equal the SP at the higher temperature T_2 then the salt must decrease in solubility with increase in temperature.

Equation (3) will not be valid unless both these variations of solubility with temperature hold true. The ratios of the SP's certainly vary, but this variation cannot be related to precipitation as done by Verhoogen except under these special conditions.

Thus these SP relations do not explain why ZnS precipitates before PbS and the precipitation must be controlled by other factors such as the pH of the precipitating solution, complex ion formation, precipitation from the vapor phase etc.

NORMAN STREET

UNIV. OF ILLINOIS,
URBANA, ILL.,
March 20, 1958

REFERENCE

Verhoogen, Jean, Thermodynamics of a magmatic gas phase: Bull. Dept. of Geol. Sci. (Univ. of Cal. Pub.) v. 28, no. 5, 91–136 (1949).

LOCALIZATION OF ORE DISTRICTS

In 1941, Billingsley and Locke (1) concluded that "the position of districts (ore) has been determined by the patterns of North American orogenic belts which make crossroads in the Rocky Mountains and blocks of superimposed deformation in Sierra Nevada, Northwest Coast and Canadian Coast Ranges."

Menard (3) has described four great "fracture zones" which follow great circle routes in the northeastern Pacific Basin. The zones, about a mile high, range from 1,400 miles to 3,300 miles in length and have an average width of 60 miles. Three of the "fracture zones" can be traced on to the North American continent. One, the Murray fracture zone cuts the coast line near Los Angeles and its continental continuation is the Texas Lineament of Moody and Hill (4). Menard postulated that a "fracture zone" would pass onto the

North American continent at the Olympic Peninsula. The Couer d'Alene lineament is probably the eastern continuation of this postulated "fracture zone." Major ore deposits are grouped along and near the lineaments.

In Peru a regional change in the strike of folded rocks between Huancavelica and Morococha is about 650 miles from a pronounced strike variation in the Jequetepeque valley. These regional changes in strike are locii of ore deposition. Possibly large fracture zones similar to those described by Menard are present in the Southeastern Pacific Basin and the regional changes in strike of folds on the mainland represent the eastern continuation of the fracture zones.

Brongersma-Sanders (2) correlated the occurrence of redwater and maximum fish mortality to the upwelling of cold ocean currents. Along the western coastline of the Americas Brongersma-Sanders recorded maximum fish mortality at latitudes that correspond to the places where "fracture zones" and probable "fracture zones" cut the coastline.

More data is needed but it is the writer's opinion that the "fracture zones" form the deep ocean trenches that localize upwelling and are major factors in the shaping of orogenic belts, and consequently the pattern of ore districts.

H. J. WARD

97 ULLAPOOL ROAD,
MOUNT PLEASANT,
WESTERN AUSTRALIA,
April 18, 1958

REFERENCES

1. Billingsley, Paul, and Locke, Augustus, 1941, Structure of ore districts in the continental framework: Am. Inst. Min. Met. Eng., Trans., v. 144, p. 9–59.
2. Brongersma-Sanders, M., 1948, The importance of upwelling to vertebrate paleontology and oil geology: ————————.
3. Menard, Henry, 1955, Deformation of the northeastern Pacific basin and the west coast of North America: Geol. Soc. America Bull., v. 66, p. 1149–1198.
4. Moody, J. D., and Hill, M. J., 1956, Wrench-fault tectonics: Geol. Soc. America, Bull., v. 67, p. 1207–1246.

Economic Geology
Vol. 53, 1958, pp. 620–625

DISCUSSIONS

ON THE OCCURRENCE OF URANIUM IN ANCIENT CONGLOMERATES[1]

Sir: It is difficult to analyze the publication of C. F. Davidson "On the occurrence of uranium in ancient conglomerates," ECON. GEOL., Vol. 52, p. 668–693, 1957. A paper that confronts facts with "considerations of mineralogy and geochemistry" has the character of a theosophical controversy, especially if the "considerator" has had no weighty experience in this field.

One is surprised at the energy and expenditure of time spent by a professor to display his negativistic attitude toward certain microscopic observations. One should, however, be disconcerted about misquotations of the literature, and I shall discuss only some of these. More could be pointed out.

Page 677, line 16 from bottom: Davidson claims that I (p. 41 of my paper) have said: that "the whole detrital" assemblage was derived from the erosion of an infinite (unendlich) number of hydrothermal veins, probably from an array of veins of several different paragenetic types" (translation by Davidson). This "quotation" evidently should cause disagreement between Liebenberg and me. But this statement of Davidson is unfortunate as he does not quote my whole sentence, which is very carefully worded: Die Herkunft der Elementparagenese scheint mir eher polygen als von einem Gangtypus ableitbar zu sein" (The origin of the primary (?) paragenesis appears to be more complex than derivable from only one type of vein. J. W. G.). After enumeration of the plausible possibilities of paragenesis I emphasized expressly: "But we know nothing about it."

Page 679, first line: Davidson says "Thus he claims repeatedly and unequivocally that uraninite and thucholite are restricted to the bottom of the reefs." In my paper I say, indeed, in many places that the principal enrichment of uraninite and gold occurs mostly in the lowest horizons (a matter which is so well known that it is almost trivial to mention again). But I also state in nearly all places (e.g., pages 14, 22, 25, 29) that this is a rule to which plenty of exceptions exist. I even picture such a case (Fig. 8, Plate II).

Page 679, line 7: "Ramdohr even casts doubt on an observation (by the consulting geologist!) that Babrosco thucholite may be concentrated not solely at the base of the reef, but at the top, the middle or the bottom." As a matter of fact, I say exactly the opposite, that I do *not* doubt his statement though it may apply only locally and certainly must not be thought the normal occurrence.

[1] Translated by John W. Gruner, University of Minnesota.

Page 681, middle: "Ramdohr, who previously (54, p. 821 [this refers to his book "Die Erzmineralien und ihre Verwachsungen," Edition 1950]) listed ilmenite and magnetite as typical of the Rand paragenesis, now shows that magnetite has very rarely been preserved and ilmenite only rarely." It is true that magnetite is mentioned here in connection with Witwatersrand. This reference at this place is, however, a part of the index of my book in which the minerals and their relations to the deposits, and vice versa, are enumerated. It refers to page 168 of my book where it is expressly stated and illustrated that the original magnetite of the Black Sand occurs now only as pseudomorphs of pyrite after magnetite which is exactly what I show in Figures 20, 21, 22 and 23.

Page 681: It is asserted that I had stated that rutile had migrated into the footwall ("is said to have migrated considerable distances even into the footwall" C. F. D.). This statement cannot be found in my paper. Regarding the migration of rutile, I merely said that originating from relatively large accumulations it migrates in some cases into pyrite pebbles perhaps to a depth of one millimeter. Personally I do not call this "considerable" distance, but this is a relative term.

Davidson evidently attempts by giving page numbers, to suggest to the reader that he does not need to look up the original (a relief for readers who do not understand German), and in this confidence, he (Davidson) may translate my passages in a suitable manner.

I am always willing and ready to submit my findings to anyone. I know that the described facts will stand up under critical scrutiny and probably be convincing arguments in this problem of genesis.

A prerequisite for such an examination and study is, however, that the person concerned has a fair knowledge of microscopy and mineralogy—one does not like to read Homer with someone who does not know the Greek alphabet—also the person must not be prejudiced in favor of his own ideas.

A comparison of the ores of the Witwatersrand, of Blind River, of the Dominion Reef, and of occurrences similar to these is the subject of an extensive paper which will probably go to the printer in April; in addition an almost word for word translation into English of my first Witwatersrand paper will be published shortly; these will give readers of English a first hand acquaintance with my work and will enable them to form an independent judgment in these controversies.

PAUL RAMDOHR

UNIVERSITY OF HEIDELBERG,
GERMANY,
March 20, 1958

ON THE OCCURRENCE OF URANIUM ANCIENT CONGLOMERATES

Sir: In his article, "On the occurrence of uranium in ancient conglomerates" (THIS JOURNAL, v. 52, p. 668–693, 1957), C. F. Davidson's considerations of statements made by us in another reference (G. S. A. Bull.,

v. 67, p. 1663, 1956) were somewhat inconsistent and erroneous. He cited the above mentioned reference of ours as the basis for saying, "In all normal sedimentary rocks (phosphorites, marine black shales, and some limestones excepted) the thorium content is much in excess of the tenor of uranium; and in highly weathered sediments such as sandstones and conglomerates the thorium:uranium ratio is commonly 10:1 or more." Referring to the uranium and thorium contents in Precambrian banket reef sediments, Mr. Davidson wrote, "More recently Adams and Pliler have maintained that the high uranium:thorium ratio in such sediments is indicative of the presence of a reducing atmosphere in Precambrian times. This circle of argument has validity only if the uranium is alluvial, and this demands acceptance as a truism of the very point that is in dispute." Actually, in our reference the banket reef deposition dispute was not referred to at all because our main interest had been in limestones and shales. We stated that more recent sediments show a wide range of thorium:uranium ratios and that, if weathering under the early Precambrian atmosphere did not oxidize uranium, a much smaller range of thorium:uranium ratios *might* be expected to some extent in all types of sediments.

The reference in question is an abstract and by its very nature is perhaps vague. However, we would call attention to the title of the abstract, "The Geochemistry of the Actinides as a Possible Clue in Interpreting the Development of the Earth's Atmosphere." A more recent and complete discussion of thorium and uranium in Cambrian and subsequent sediments appears in a recent article (Bull. A.A.P.G., v. 42, 1958) by J. A. S. Adams and C. W. Weaver entitled, "Thorium-to-uranium ratios as indicators of sedimentary processes: Example of the concept of geochemical facies."

Dept. of Geology,
The Rice Institute,
Houston, Texas,
Apr. 5, 1958

John A. S. Adams
Richard Pliler

ORE GENESIS—THE SOURCE BED CONCEPT

Sir: In connection with C. L. Knight's article (Econ. Geol., v. 52, p. 808–817) proposing a Source Bed Concept of Ore Genesis, recent regional mapping of a mineralized area (Luiri Hill) some 150 miles southwest of the Northern Rhodesia Copperbelt has re-affirmed that metamorphism of the Katanga System (to which the Copperbelt host-rocks belong) increases southward towards the post-Katanga granite exposed in the Hook of the Kafue River. The monzonitic margins of the granite have assimilated major amounts of lime from the adjoining Middle Katanga limestone. Carbonate beds have been altered to calc-flinta at igneous contacts. Large-scale iron metasomatism has produced iron-rich skarn-rocks and contact metasomatic iron-oxide bodies in a scapolite-rich contact zone. These bodies are high-temperature products

containing much magnetite with local apatite and interstitial thorite. They are abundant in a narrow zone about 100 miles in length known locally as the Lusaka-Mumbwa ironfield. Drilling has proved that these iron oxides are veined by pyrite and chalcopyrite.

Thirty miles northeast of the magnetite-monzonite zone, specularite persists in fault and shear zones, and many quartz and carbonate veins contain copper and iron sulfides accompanied by minor gold and silver. Adjoining this cupriferous zone to the southwest, a highly greisenized and tourmalinized gold area of about 140 square miles contains much auriferous pyrite in quartz veins, with subsidiary chalcopyrite, silver, and bismuthinite; faulting and lithological contacts have strongly favored ore concentration at the Matala and Dunrobin gold mines.

Concerning the cupriferous zone, some geologists have commented upon the close similarity between the copper-bearing Katanga shales at the (abortive) Lewis Mine and the Copperbelt ore-shales, inferring that the former must also be of syngenetic origin. The results of recent regional mapping (Rept. No. 4, Geol. Surv. of N. Rhod.) and commercial drilling (op. cit.) do not support this inference however. The Lewis and nearby copper prospects occur near the distorted prow of an isoclinally-folded syncline where copper sulfides are dispersed in numerous shear zones, some of which (e.g. Lewis Mine) cut the bedding at such low angles as to cause a resemblance to truly bedded deposits. From the aspect of ore-concentration, the relatively undisturbed portions of the north limb have proved more favorable than the distorted prow of the syncline: a sub-economic ore-body has been traced for several miles along a constant stratigraphic horizon on the north limb.

In this case, Daly's Hypothesis suggests the basis of a theory of ore-genesis that seems more in accordance with the broader field evidence than does the Source Bed Concept.

KENNETH A. PHILLIPS

GEOLOGICAL SURVEY, NORTHERN RHODESIA,
LUSAKA, N. RHODESIA,
Feb. 11, 1957

ORE GENESIS—THE SOURCE BED CONCEPT

Sir: The presentation by C. L. Knight of his source bed concept of ore genesis, in ECONOMIC GEOLOGY for November 1957, includes the Bathurst copper-lead-zinc field of New Brunswick, Canada, as an example of a camp where a particular sedimentary bed was important in localizing ore. The removal of this camp from his list of stratigraphically controlled ore fields might be, at least, considered for the reasons briefly outlined below:

(1) The Keymet, New Larder "U," Kennecott Clearwater, Nigadoo and Sturgeon River pyrite-galena-sphalerite deposits of the Bathurst camp lie geographically *outside* the "circular area 25 miles in diameter"—within which presumably lies the exclusively favorable bed. The Nigadoo, Keymet and

Sturgeon River bodies are vein deposits. The others are replacements. They are relatively small sulfide bodies. However, any general ore genesis theory applied to this camp cannot ignore them. There seems no possible way that the source-bed theory could apply to these sulfide bodies as any attempt to align these bodies on or near a common source-bed would involve structural impossibilities.

(2) Wilson, Russel and Farquhar (J. T. Wilson, R. D. Russel and R. M. Farquhar, Can. Inst. of Mining and Met., Transactions, Volume LIX, 1956 p. 310–318) made isotopic age determinations on some of the ores of the Bathurst Camp as well as other lead camps throughout Canada. Their general conclusions were that the ratios of radiogenic lead isotopes relative to lead 204 "(have) been interpreted to mean that the lead ores have risen from a uniform source. Since the composition of the crust is far from uniform this source is presumably below the earth's crust. . . ." "Crustal rocks, whether sedimentary or igneous do not show this uniformity and therefore it is concluded that normal lead ores are juvenile and have risen from the mantle of the earth along faults. Their rise may in many cases have accompanied igneous activity. Their deposition need not have been a simple and direct process, but the uniformity of lead isotope ratios does seem to rule out the possibility that ordinary lead ores have spent hundreds of millions of years in heterogenous crustal rocks." This uniformity would also seem to rule out the possibility that Bathurst ores were remobilized from a source-bed.

(3) There are important strong major faults that bounded the field to the North and West and other suspected North-South faults that cut across the whole camp. Folding, on a major and minor scale, was active in the district. The host rocks are metamorphosed to varying degrees, but, in general, regional metamorphic effects are very conspicuous near sulfides.

(4) Holyk, whose paper was quoted, says elsewhere in the paper used by Knight—"The writer does not imply that all the sedimentary formations are continuous between the areas in which they are definitely known to occur." Knight's statement, taken from Holyk's paper, that the sulfide bodies are located at the contact of a quartz porphyry with one of the sedimentary units seems to be overgeneralized. Some broad trends and thick petrologic units can be traced near the indented irregular rim of the "circle," but the detailed stratigraphy within the circular area and to the south and west, is not known. Extreme paucity of outcrop, metamorphic and facies changes on strike and possible sharp concealed fold structures make stratigraphic mapping difficult and interpretations uncertain.

(5) On the east and south parts of the rim of the circle there are a number of major deposits that at first glance would appear to fit the source-bed theory. These are the deposits of the Heath Steel Mines, the Brunswick and the Anacon deposits. Admitting there may be a recognizable common throughgoing stratigraphic unit related to these bodies, there would however remain the problem (among others) of the recently discovered Headway deposit. This is a relatively small body but it has sulfide mineralogy similar to the other sulfide bodies of the camp. This body lies, at least, several thousand

feet stratigraphically below any possible source-bed common to the above deposits.

There is little doubt that the Bathurst area was the scene of intense volcanic activity during the depositional stage and later a focus of transverse tectonic adjustment during and after the orogenic stage of the Appalachian geosyncline. During the orogenic or post-orogenic stages deep structural intersections could have tapped conventional granitic magmatic fluids or deeper sulfide-bearing fluids from the mantle, and the sulfide bodies could have formed in appropriate structural traps.

All sulfide bodies so far discovered at Bathurst camp have been associated with known or inferred local fold or fault structures and are located near deep indentations and embayments of the regional structural "dome." Granites and granitization products are nearby. Possibly further study may even show regional zoning. These are the standard structural elements usually demanded by the hydrothermalists. A syngenetic theory, however modified, seems to be the weakest general ore genesis theory applicable to this camp.

MARTIN D. KIERANS

450 RIVERSIDE DRIVE,
WEST BATHURST, NEW BRUNSWICK,
April 3, 1958

Economic Geology
Vol. 53, 1958, pp. 626–635

REVIEWS

An Introduction to Graphic Solutions of Geologic Structures—Laboratory Exercises and Problems. By A. Norman MacIntosh. Pp. 78; pl. 26; 19 ruled work sheets. Edwards Brothers, Inc. Ann Arbor, 1958.

Mr. MacIntosh has revised and combined his "Introduction to the Interpretation of Geologic Maps and Structures" and his "Graphic Solutions of Geologic Structures," under this new title.

The result is a laboratory text which is admirably suited to the task of giving the geologic student a thorough understanding of the three dimensional relationships between geologic structures such as folds and faults and their sometimes surprising outcrop patterns.

All of the pages are perforated for easy removal. The plates and their respective questions are printed on one side of the page, which lends itself to classroom use.

The 26 plates are arranged in order of increasing difficulty, starting with a simple contouring problem and ending with "A and B are points on different levels in a mine having elevations as shown. From B a drift extends N 35° W up a 5 percent grade. It is proposed to drive a crosscut from A, down a 7 percent grade, to intersect the drift from B. 1. Determine the bearing and the length of the crosscut from A. 2. Determine the elevation at the point of intersection."

Incidentally, this last is an excellent example of the ease with which many problems can be solved graphically which would otherwise involve calculus.

All of the problems illustrate techniques and principles that should be familiar to every geologist. A few of the questions, since they involve economic factors such as lengths of drill holes and costs of different methods of developing an ore body, are of more direct interest to the economic geologist.

The written part of the text contains a clear plate-by-plate explanation of the graphic method or methods that can be used in solving each problem. Since this part of the text is also perforated, some teachers may prefer to remove the written explanations in order to use the corresponding plates for test purposes or to encourage the student to try figuring them out in his own way before referring to the explanation.

Alan T. Broderick

Inland Steel Co.,
Ishpeming, Mich.,
May 20, 1958

The Future Supply of Oil and Gas. By Bruce C. Netschert. Pp. 134. The Johns Hopkins Press, Baltimore, 1958. Price, $3.00.

The title also states that this book is "a study of the availability of crude oil, natural gas, and natural gas liquids in the United States in the period through 1975." It is published for "Resources for the Future, Inc.," a non-profit corporation supported by the Ford Foundation, interested in research and education regarding natural resources. The author, formerly on the staff of the President's

Materials Policy Commission (Paley Commission), is a research associate in the energy and minerals area of Resources for the Future. This study is to be incorporated into a larger volume, to be published later, on the over-all United States energy position through 1975.

Under the headings of crude oil, natural gas, and natural gas liquids, the author considers estimates of reserves, future capacity and production, technology, availability, and other sources of supply.

The general conclusions are that in the United States and its continental shelves there are around 500 billion barrels of oil, and 1.2 quadrillion cubic feet of natural gas, which quantities, however, will not necessarily be discovered or extracted, but are believed to exist. The author forecasts from an economist's viewpoint and sets up his own concepts. His study is based upon the analysis and interpretation of facts and opinions. During it he conversed with many oil company officials and technicians.

The author considers that in 1975 the indicated total domestic availability of crude oil in the United States will be 4 billion barrels of primary oil and 2 billion barrels of secondary oil. He points out, however, that these figures are not predictions of production but what *could* be produced. The author adopts the A.G.A. figure of 22.5 trillion cubic feet of natural gas as the availability for 1975 with net availability 10 to 15 percent lower. Also, for natural gas liquids, 1 billion barrels are considered to be available for 1975, although there may not be a market for this amount.

The Atomic Age and Our Biological Future. By H. V. Brønsted. Pp. 80. Philosophical Library, New York, 1957. Price, $2.75.

This little booklet was translated from Danish by E. M. Huggard. The author is Professor of Zoology at the University of Copenhagen, and this work is based on a series of lectures to the general public. In Chapter I he discusses the various kinds of radiation, and in the next two chapters, the fertilized egg and mutations. He then takes up his main theme, discussing the effects of radiation on the body, on sterility, embryonic development, man's genetical constitution, transmission of genes, and deleterious mutations. The last chapter deals with isotopes. Under these headings are described simply, with a minimum of technical language, the biological and genetic effects that may come from the increasing rise of atomic energy if measures are not taken to make sure that radiation from the atmosphere does not rise above the level that can be tolerated without damage to the human body.

The author believes that from the standpoint of future generations hydrogen bomb tests are unjustified.

Engineering Geology Case Histories No. 2. Parker D. Trask, Editor. Pp. 43. Prepared for the Division on Engineering Geology of the Geological Society of America, New York, 1958.

The purpose of this report, and of the predecessor No. 1, is to present descriptions of the geological problems involved in engineering construction problems. This is done by a series of short individual case histories written by selected authors.

There are 11 such case histories as follows: Tunnel construction in Mancos shale, Colorado, by R. A. Bohman; Summary of six Rocky Mt. cases, by C. S. Content; Foundation grouting, McNary Dam, Oregon and Washington, by R. L. Gullixson; Antonio Lucchetti dam, Puerto Rico, by C. A. Kaye; Mississippi-Atchafalaya diversion, La., by C. R. Kolb; Cement-aggregate reaction, by K.

Mather; Dam-site studies from aerial photos, by J. D. Mollard; Artificial recharge of ground-water in Calif., by R. C. Treacher; Hydro-electric power system, Austria, by E. M. Winkler; Causes of Sear's Point landslide, Calif., by H. D. Woods.

Each of the cases is clearly and briefly described, averaging about 4 pages each. They make good reference material for the practicing geologist and the student.

Principles of Geodynamics. By Adrian E. Scheidegger. Pp. 280; figs. 86. Springer-Verlag, Berlin, 1958. Price D.M. 49.60.

The author of this book received a Ph.D. from Toronto, and a diploma from Zurich. He is now Research Associate with the Imperial Oil Co. in Calgary, Alberta.

In the first two chapters, Physiographic and Geologic Data Regarding the Earth, and Geophysical Data Regarding the Earth, the author summarizes the known physical facts regarding the earth. These include such subjects as geological evolution, geomorphology, continents and oceans, faults and folds, gravity and seismological data, layering of the earth, age determinations, thermal data, magnetization, and geochemical data. The following chapters are: III. Mechanics of Deformation; IV. Effects of Rotation of the Earth; V. Continents and Oceans; VI. Orogenesis; VII. Dynamics of Faulting and Folding; VIII. Dynamics of Other Features, such as meteor craters, boudinage, domes, volcanism, and postglacial uplift. The last five, as will be seen from their tables, give a synoptic view of the broad subjects.

The author gives "an evaluation of existing ideas in the light of presently available facts" which has not been done before for all of the various hypotheses. The author points out that most articles on the subjects have been written to advance one or other of the hypotheses as the true one. Consequently he became an agnostic and examines critically the most competent presentations, looking for proof of one or another of the ideas. This he has done successfully.

The book will serve as an advanced text book, and as a general reference in this field of earth sciences, which every geologist interested in geodynamics and structural geology will want to have in his library.

Geologie und Bodenschatze Afrikas. By Erich Krenkel. Pp. 598; figs. 158. Akad. Verlagsgesellschaft Geest and Portig K.-G. Leipzig, 1957. Price, D.M. 61.

An up-to-date book on the geology of Africa is much needed, but is a large undertaking. This book attempts to do this in condensed form. It is of course a large area to cover.

The book is divided into two parts; Part I, of 506 pages, is devoted to the geology, and Part II, of 59 pages, deals with the mineral wealth.

For the discussion of the geology the author divides the continent into geographic and partly geomorphologic areas. It opens with the Atlas regions and considers 9 subdivisions, including the coastal region, the High Atlas, the High Plateaus, Algeria, Morocco, the Riff, and the Paleozoic. Next to follow are the Sahara regions, Red Sea Graben, Syrabien, the northeast area, East Africa, Madagascar, southern Africa (including the Congo), Guinea-Sudan, Atlantic Islands, and Africa in Retrospect. The last includes Gondwanda lineations, magmatic ac-

tivity, and historical geology. Part I gives a very brief picture of the ore and non-metallic deposits of this rich continent, including as it does the great chrome, iron, gold, copper, cobalt, uranium, and platinum deposits and the extensive diamond and asbestos deposits. Each part is followed by an extensive index. At the end there are 24 pages of references divided for parts I and II, and subdivided according to regions and countries.

It will make an extremely handy reference to African geology for those who read German.

The Mineragraphy of the Radium Hill Uranium Deposits and the Delineation of the Whip and Geiger Lodes. By Richard F. LaGanza. Pp. 21; figs. 35; colored maps 3. Dept. of Mines, South Australia, 1957.

This mimeographed report brings up-to-date information made available subsequent to previously published investigations and contains a detailed microscopic study by reflected light of the complex ores of this deposit.

The deposits consist of hypogene replacement lodes along anticlinal axial plane shares in folded Archean gneisses. The ore occurs in definite shoots which pinch and swell and include horses of waste. The walls are prominently sericitized.

The ores consist of rutile, ilmenite, magnetite and davidite with subordinate magnetite, pyrite, chalcopyrite, and molybdenite. The earliest minerals are the oxides, which exhibit exsolution phenomena, followed by pyrite. Next there was selective replacement of these minerals by davidite, followed by pyrite and chalcopyrite stringers and a little molybdenite. The davidite (complex iron-titanium-lanthanum-uranium oxide) occurs as disseminated grains, as stringers and as masses. Thirty-four photomicrographs illustrate the ore mineral relations. The colored maps show plans and sections of the lodes.

Introduction to Geology. By Howard E. Brown, Victor E. Monnett and J. Willis Stovall. Pp. 644. Ginn and Co., New York, 1958. Price, $7.25.

The authors state that this new textbook is intended to serve the needs of students who wish a broad education rather than for those who plan a future geological career. In this respect it has achieved its purpose for it is clearly and simply written and extremely well illustrated.

Part I (382) pages) takes up the principles of physical geology in which the authors attempt to interest the student in the common everyday features one sees in travelling. It includes the customary subjects of physical geology—the earth, weathering, running water, ground water, oceans, atmosphere, glaciation, landscapes, diastrophism, mountains, vulcanism, rocks and minerals, and mineral wealth. The last deals with coal, oil and gas, a few metallic deposits, and non-metals (22 pages). The various chapters are well illustrated with drawings and photos.

In Part II, Historical Geology, first comes astronomy, then geologic time, origin of life, organic evolution, fossils, plant and animal kingdom, paleography, correlation, the geologic areas, and man. Lists of collateral reading are given after each chapter. An appendix gives some basic facts about the earth, cross sections of geologic structures of North America, and portions of several typographic maps.

This one adds another book to the growing list of elementary text books of geology, among which there will be keen competition. This one should hold its place.

BOOKS RECEIVED

JAMES M. ALLEN

Concise International Dictionary of Mechanics and Geology, English-French-German-Spanish. S. A. COOPER. Pp. 400. Philosophical Library, New York, 1958. Price, $6.00. *English words and phrases are followed by the French, German and Spanish equivalents; a French, German and Spanish index of words in those languages refers to page and line of the definitions in the English Dictionary. Very convenient.*

Mineralmacht Brasilien. HANNFRIT PUTZER. Pp. 129; figs. 11. Deutsch-Brasilianische Handelskammer in São Paulo, São Paulo, Brazil, 1956. *Location and description of mineral deposits in Brazil.*

First Annual Report of the International Tin Council 1956–57. Pp. 35. International Tin Council, London, 1958. Price 7s. 6d. or U. S. $1.00. *Fiscal report including membership, meetings, pricing, etc., of tin.*

The Geology and Mineral Resources of the Upper Rajang and Adjacent Areas Sarawak. H. J. C. KIRK. Pp. 168; pls. 53; figs. 29; tbls. 30. Geological Survey Dept., British Territories in Borneo, Mem. 8, Kuching, 1957. Price, 21 sh. *Areal geology of jungle area in central Sarawak underlain by Tertiary sediments and volcanics. Bituminous type coal of Miocene age may prove economic if markets can be found.*

Variations in Isotopic Abundances of Strontium, Calcium, and Argon and Related Topics. Pp. 167; pls. 3; figs. 14; tbls. 43. Fifth Annual Progress Rept. for 1957–58, U. S. Atomic Energy Commission, Cambridge, Mass., 1958. *Results of age measurements in North and South America, Africa and Australia. Studies on glauconite and list of glauconite specimens from the world from Precambrian to Recent suitable for dating.*

Geochemical Prospecting. N. R. MUKHERJEE and L. M. ANTHONY. Pp. 81; pls. 7; tbls. 6. University of Alaska School of Mines Bull. 3, College, Alaska, 1957.

Lexique Stratigraphique International. Vol. V. Amérique Latine. Fas. 7. Chile. Pp. 445; fig. 1. *Descriptions of stratigraphic units recognized in Chile; Precambrian to Recent. Geological map of Chile. Scale, 1 cm.: 50 kms.* Centre National de la Recherche Scientifique, Paris, 1957.

On the Paragenesis of Copper Ores. PAUL BARTHOLOMÉ. Pp. 31; fig. 1; tbls. 3. Studia Universitatis, «Lavanium», Leopoldville, 1958. *Discussion of the systems Copper-iron-sulphate, organe bornite-vallerite and the role of sulphur in the paragenesis of copper minerals. In English.*

California Journal of Mines and Geology, Vol. 54, No. 1. Pp. 177; figs. 6. Price, $1.00. Department of Natural Resources, San Francisco, 1958. *Annual report of the State mineralogist; mineral production and consumption statistics.*

Lower Tertiary Foraminifera from Contra Costa County California. BERNICE YOUNG SMITH. Pp. 83; pls. 32; figs. 3; tbls. 2. University of California Publ. in Geological Sciences, Vol. 32, No. 3. Berkeley, 1957. *One hundred and eighty-one species of fossil foraminifera are described. Inferences drawn that enclosing strata were deposited at medium depths under tropical to sub-tropical surface temperatures.*

Metal and Industrial Mineral Mines in Canada. Pp. 34. Price, 25 cents. Dept. of Mines and Technical Surveys, Ottawa, 1957. *Type, location, production of mines in Canada.*

Geološki Glasnik 1955 Bulletin Géologique. Pp. 213; pls. 33; figs. 45; misc. tbls. Zavod za Geološka Istraživanja i Ispitivanja Gradevinskih Materijala, Sarajevo, 1958. *Various papers on economic geology, mineralogy, petrology, and stratigraphy. In Jugoslavian; German summaries.*

Memoria Sui Giacimenti Italiani di Manganese. C. E. BURCKHARDT and F. FALINI. Pp. 221–272; pl. 1; figs. 7; tbls. 8. XX Congreso Geológico Internacional Symposium Sobre Yacimientos de Manganeso, Tomo V, Europa, México, 1956.

Boletin del Centro de Documentacion Cientifica y Tecnica de Mexico. Vol. VI, No. 7. Pp. 36. Secretaria de Educacion Publica, Mexico City, 1957. *Bibliography of papers in mathematics, astronomy, astrophysics, physics, geology, geophysics and geodesy.*

1957 Oil and Gas Developments in Ohio. GEORGE C. SHEARROW. Pp. 27; figs. 2; tbls. 14. Ohio Geological Survey, Rept. of Invest. 36, Columbus, 1958. *Oil production up 800,000 barrels; gas production up 534,000,000 cubic feet even though new wells declined by 9%.*

Pennsylvania Underclays—Potential Bonding Clays for Use in Foundries. HAYDN H. MURRAY. Pp. 27; figs. 6; tbls. 6. Price, 50 cents. Indiana Dept. Conservation, Geological Survey Rept. of Progress 11, Bloomington, 1957. *Describes 5 areas in Indiana from which clay suitable for foundry bonding occurs.*

Memorandum Concerning Mining Possibilities in Perú. M. S. BOGGIO. Pp. 68. Mario Samame Boggio, Lima, 1957. *Brief summary of economic and mining situation in Peru. In English, French, German, Spanish and Portuguese.*

Publicaciones del Departamento de Cristalografia y Mineralogia. Pp. 44; figs. 26; tbls. 4. Museo Nacional de Ciencias Naturales, Madrid, 1957. *Various papers on crystallography and x-ray diffraction techniques.*

List of Publications and Maps. Pp. 38. Virginia Division of Mineral Resources, Charlottesville, 1958.

Pycnaspis Splendens, New Genus, New Species, A New Ostracoderm from the Upper Ordovician of North America. TOR ØRVIG. Pp. 23; pls. 3; figs. 5. Proceedings of the United States National Museum, Smithsonian Institution, Vol. 108, No. 3391, Washington, 1958. *Description of a new ostracoderm from the Upper Ordovician of the eastern slopes of the Bighorn Mountains in Wyoming.*

Bureau of Mineral Resources, Geology and Geophysics—Australia, 1957–1958.

Summ. Rept. 38. Tin. J. F. IVANAC, J. BARRIE, H. F. PEARSON, and Z. KALIX. Pp. 34; figs. 3; tbls. 14. Price, 3 sh. *Uses, occurrence, production, prices, etc., of tin in Australia.*

The Australian Mineral Industry—Quarterly Review and Quarterly Statistics. Vol. 10, No. 3. Pp. 84; tbls. 20. Price, 3 sh. *Statistics of mineral production and utilization.*

Bull. 41. Lower Permian Pelecypods and Gastropods from the Carnarvon Basin, Western Australia. J. M. DICKINS. Pp. 52; pls. 10; figs. 9. *Occurrence, distribution of pelecypods and gastropods. A new genus of pelecypoda erected for lower Permian forms.*

Universidad de Chile Facultad de Ciencias Fisicas y Matematicas Instituto de Geologia—Santiago, 1956.

Publ. 7. Erupción del Volcán Nilahue. CAUPOLICÁN COFRÉ ZUNIGA. **Las Capas Volcánicas de Carrán y la Erupción del Nilahue.** LEONEL LEÓN and

ENRIQUE POLLE. Pp. 131; pls. 18; figs. 9; tbls. 10. *Two papers describing the eruption of a volcano in southern Chile in 1955, and the resulting rocks. In Spanish.*

Publ. 8. Primeras Noticias Sobre la Existencia del Paleozoico Superior en el Archipiélago Patagónico Entre los Paralelos 50° y 52° S. GIOVANNI CECIONI. Pp. 19; figs. 8. *Brief descriptions of Permo-Carboniferous strata on the islands off southern Chile. In Spanish.*

Publ. 9. Fauna del Cretáceo Inferior de Copiapó. JUAN TAVERA. Pp. 11; pl. 1. *Description of the fauna of the lower Cretaceous rocks of Chile. In Spanish.*

Illinois Geological Survey—Urbana, 1957–1958.

Circ. 246. Influence of Coking Time on Expansion Pressure and Coke Quality. H. W. JACKMAN, R. L. EISSLER, and R. J. HELFINSTINE. Pp. 26; figs. 16; tbls. 11.

Circ. 248. Groundwater Geology in East-Central Illinois. A Preliminary Geologic Report. LIDIA F. SELKREGG and J. P. LEMPTON. Pp. 36; figs. 7. *Includes a general summary of groundwater principles, controlling geologic factors, and methods of development. Ground water supplies in central Illinois range from poor to excellent.*

Circ. 249. Stratigraphic Policy of the Illinois State Geological Survey. H. B. WILLMAN, DAVID H. SWANN, and JOHN C. FRYE. Pp. 14. *A system of multiple classification in which rock-stratigraphic, time-stratigraphic, bio-stratigraphic, cyclical, facies, and soil-stratigraphic units are discussed.*

Circ. 250. Fishhook Gas Pool, Pike and Adams Counties, Illinois. WAYNE F. MEENTS. Pp. 15; figs. 2; tbls. 3. *Description of gas pool in Silurian rocks in western Illinois. Pool presently shut down for lack of markets.*

Rept. of Investigations 202. Vanadium Efflorescence and Its Control by the Use of Fluorspar. D. L. DEADMORE, A. W. ALLEN, and J. S. MACHIN. Pp. 29; figs. 11; tbls. 10. *A study of the effect of fluorspar on the formation of water-soluble vanadium compounds in clays.*

List of Publications. Pp. 40; figs. 3.

Consiglio Nazionale delle Ricerche—Rome, 1957.

Centro di studio per la geologia tecnica. Attività svolta dal 1° Novembre 1955 al 31 Ottobre 1956. Pp. 56; figs. 21.

Relazione sui lavori della Associazione Vulcanologica e della Associazione de Idrologia Scientifica. Pp. 35. *Report of meetings of the International Union of Geodesy and Geophysics in Toronto, September, 1957. In Italian.*

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1957.

Rept. 175. Variation in Crystal Habit of Pyrite. ICHIRO SUNAGAWA. Pp. 42; pls. 10; figs. 16; tbls. 9. *Crystal habit controlled by environment and supply of solution. Impurities considered to be of secondary importance. In English.*

Explanatory Text of the Geological Map of Japan. Akaho (Kanazawa-74). M. MURAYAMA and M. KATADA. Pp. 57; pls. 17; figs. 5; tbls. 6. *Areal geology of metamorphic terrain in central Japan. Map, scale 1:50,000. English abstract.*

Explanatory Text of the Geological Map of Japan. Obama (Kyōto-3). O. HIROKAWA, H. ISOMI, and K. KURODA. Pp. 39; figs. 4; tbls. 5. *Areal geology of an area in central Japan. Small deposits of cupriferous pyrite, nickel and chromite, and manganese. Map, scale 1:50,000. English abstract.*

Missouri Geological Survey—Rolla, 1957–1958.

Rept. of Investigations 23. Study of Missouri Shales for Lightweight Aggregate. P. G. HEROLD, P. KURTZ, JR., T. J. PLANJE, and J. D. PLUNKETT. Pp. 39; figs. 11; tbls. 5. *Of 55 samples of shales, clays and loesses 12 appear suitable for commercial use.*

Bibliography of the Geology of Missouri 1956. JOHN W. KOENIG. Pp. 48.

Bibliography of the Geology of Missouri 1957. JOHN W. KOENIG. Pp. 35.

Montana Bureau of Mines and Geology—Butte, 1958.

Information Circ. 20. Directory of Known Mining Enterprises 1957. KOEHLER STOUT and WALTER ACKERMAN. Pp. 57; pls. 1. *Location, production, owner, operator and status of mining enterprises in Montana.*

Information Circ. 22. Barite Deposits in Montana. V. C. DEMUNCK and W. C. ACKERMAN. Pp. 29; pls. 3. *Properties, uses, prices and occurrence of barite in the U. S. Two producing properties and a number of prospects are described.*

Província de Moçambique Serviços de Indústria e Geologia—Lourenço Marques, 1957.

Bol. 21. Contribuições para o Estudo da Petrografia de Moçambique. III. Primeiro Reconhecimento Petrográfico da Circunscrição do Barué. A. BORGES and A. V. PINTO COELHO. Pp. 80; pls. 6; figs. 4; tbls. 3. *Geologic map. Results of a petrographic and field study of a region in western Mocambique underlain by volcanic, igneous and metamorphic rocks.*

Bol. 22. Minerais de Província de Moçambique. J. BÉHIER. Pp. 135; pls. 8. *Descriptive list of the minerals in the collection of the Freire D'Andrade museum.*

Bol. 23. Notícia Explicativa do Esboço Geológico de Moçambique. A. J. DE FREITAS. Pp. 69; tbls. 12; geologic map, scale 1:2,000,000. *Explanatory notes to accompany the map of Moçambique. English abstract.*

Newfoundland Department of Mines and Resources—St. John's, 1958.

Mineral Resources Development of Newfoundland. Pp. 3. *Very brief summary of activity of government and private interests in Newfoundland.*

Geological Survey Rept. 14. Geology of the Lower Gander River Ultrabasic Belt. S. E. JENNESS. Pp. 56. *Areal geology of an area in north-central Newfoundland. Mid Ordovician clastics and lavas intruded by a variety of basic and ultrabasic rocks. Geologic map, scale 1 inch : 1 mile.*

Ontario Department of Mines—Toronto, 1958.

Sixty-fifth Annual Rept. Vol. LXV, Pt. 4, 1956. Geology of the Populus Lake Area. J. C. DAVIES and S. N. WATOWICH. Pp. 24; pls. 2; figs. 6. *Fairly good copper-nickel possibilities in the area. Geologic map, scale 1 inch : ½ mile.*

Sixty-Fifth Annual Rept. Vol. LXVI, Pt. 1, 1957. Statistical Review of the Mineral Industry for 1956. M. G. ARNOLD. **Mining Accidents in 1956.** STAFF OF MINES INSPECTION BRANCH. **Classes for Prospectors, 1956–57.** W. D. HARDING. Pp. 78; pl. 1, figs. 3; tbls. 64.

Polskie Towarzystwo Geologiczne—Kraków, 1957.

Regionalna Geologia Polski. Tom III. Sudety (Praca Zbiorowa). Pp. 300; pls. 23; figs. 43; tbls. 12; maps and sections 19. *Areal study of the Sudety region of Poland. In Polish.*

Vol. XXV, Fasc. 3. Annales de la Société Géologique de Pologne. Pp. 175; pls. 9; misc. tbls. *A number of papers on the microfauna and stratigraphy of the Polish Tertiary. In Polish; abstracts in Russian, English, French and German.*

Vol. XXV, Fasc. 4. Annales de la Société Géologique de Pologne. Pp. 127; figs. 22. *A number of papers on Tertiary stratigraphy and fauna. In Polish, summaries in French.*

Vol. XXV, Fasc. 1. Annales de la Société Géologique de Pologne. Pp. 61; pls. 4; figs. 16. *Papers on Miocene sedimentation, differential thermal analysis of oxidized zinc ores, diagenetic dolomite in Carpathian Flysch. In Polish; summaries in Russian or English.*

Vol. XXVI, Fasc. 2. Annales de la Société Géologique de Pologne. Pp. 123; pls. 8; figs. 11. *Various papers on cave deposits, deposition, characteristics of flysch in Poland. In Polish; English summaries.*

Quebec Department of Mines—Quebec, 1957–1958.

Outline of Progress of the Mining Industry of the Province of Quebec During the Year 1957. EDGAR-E. BÉRUBÉ. Pp. 17; pls. 4; fig. 1; tbls. 2. *Mineral production decreased by 9.5 per cent in 1957 as compared with 1956.*

The Mining Industry of the Province of Quebec in 1956. Pp. 135; pls. 5; tbls. 61. *Production statistics for metals and non-metals in 1956.*

Mineral Resources and Mineral Industries of the Province of Quebec. Pp. 74; pls. 70; figs. 5; tbls. 5; maps 2. *General information on minerals and mineral processing.*

List of the Principal Operators and Owners of Mines and Quarries in the Province of Quebec. Pp. 94. *Names and addresses; mine locations.*

Services Géologiques du Portugal—Lisbon, 1957–1958.

Estudos, Notas e Trabalhos do Serviço de Fomento Mineiro, Vol. XII, Fascs. 3–4. Pp. 245; figs. 31; tbls. 16. *A number of articles dealing with mineral statistics, mineralogy, and well logging. In Portuguese.*

Les Dinosauriens du Portugal. L'ABBÉ F. DE LAPPARENT and GEORGES ZBYSZEWSKI. Pp. 59; pls. 36; figs. 13. Memoir 2. *Description and distribution of dinosaur fossil remains in the Mesozoic of Portugal. In French.*

Institute of Mineralogy, Paleontology, and Quaternary Geology, University of Lund—Sweden, 1958.

No. 38. Basic Metamorphic Rocks from the Region of Höljes in Northern Vermland. A Study in Progressive and Retrograde Metamorphism. PONTUS LJUNGGREN. Pp. 34; figs. 12; tbls. 19. *Description of a metamorphic suite in which progressive retrograde and metasomatic metamorphism has occurred.*

No. 40. The Soft Iron Ores of Vermlands Taberg. PONTUS LJUNGGREN. Pp. 11; figs. 2; tbls. 3. *Description of Swedish magnetite ores that have altered to goethite.*

Bureau of Economic Geology The University of Texas.—Austin, 1957.

Rept. of Investigation 31. Devonian-Mississippian Transition in Central Texas. P. E. CLOUD, JR., V. E. BARNES, and W. H. HASS. Pp. 9; pls. 5; fig. 1. *The Devonian-Mississippian transition is described and a new unit, the Houy Formation, used to describe it.*

Rept. of Investigation 32. Studies of Cenozoic Geology Along Eastern Margin of Texas High Plains, Armstrong to Howard Counties. J. C. FRYE and A. B. LEONARD. Pp. 59; pls. 5; figs. 10. *Pliocene and Pleistocene geology of an area in northwestern Texas.*

Rept. of Investigation 33. Pleistocene Equidae of Texas. J. H. QUINN. Pp. 49; pls. 7; fig. 1, tbls. 10. *Description of Pleistocene fossil remains of horses in Texas.*

Publ. 5724. Geology of Parker County, Texas. LEO HENDRICKS. Pp. 64; pls. 7; figs. 6. *Areal geology of an area in north central Texas underlain by Pennsylvanian, Cretaceous, Pleistocene and Recent formations. Small oil and gas production.*

Economic Geology
Vol. 53, 1958, pp. 636-637

SCIENTIFIC NOTES AND NEWS

DAN E. FERAY has been appointed Magnolia Petroleum Company Professor of Geology at Southern Methodist University, Dallas, Texas. The Professorship has been set up by the Magnolia Petroleum Co. to encourage and support superior undergraduate teaching.

FRANK P. SONNENBERG is chief geologist for Chaco Petroleum, S. A., Bolivian subsidiary of Tennessee Gas Transmission Co.

LEWIS G. WEEKS has retired from his position as chief geologist for Standard Oil of New Jersey. He will engage in consultation on the geology of petroleum.

FRANCIS L. PIERSON, senior geologist of U. S. Potash Co., has been promoted to chief geologist.

J. DONALD RYAN, associate professor of geology at Lehigh University, was elected president of the Eastern section, Association of Geology Teachers, succeeding DR. ERLING DORF of Princeton University.

DAVID L. COOLBAUGH is now employed as mining advisor with the Government Technical Institute in Insein, Union of Burma.

GABOR DESSAU has terminated his two years' assignment with the Technion, Israel Institute of Technology, in Haifa, where he was sent by UNESCO for the establishment of a Mineral Engineering Department. Now he is back in Italy, and is "Chargé de cours" in Mineral Deposits at the Geological Institute of the University of Pisa.

The Gold Medal of the Institution of Mining and Metallurgy for 1957 has been awarded to DR. JOHN FAIRFIELD THOMPSON, Chairman of the Board of Directors of International Nickel Co., in recognition of his distinguished services to metallurgical science, research and practice, with special reference to the nickel industry. Honorary Membership of the Institution has been conferred on MR. ROBERT ANNAN, in recognition of his outstanding services to the mining industry and to the Institution; on DR. FRANK DIXEY, in recognition of his services to the science of geology and in particular of his work in reorganizing the Colonial Geological Surveys; and on MR. MAURICE ALAN EDGAR MAWBY, in recognition of his valuable services to the mining industry in Australia and to the Institution.

The U. S. GEOLOGICAL SURVEY has published a new wall size map of the Arabian Peninsula, one larger scale geologic map, and four topographic maps covering portions of Saudi Arabia. Under joint sponsorship of the Saudi Arabian Ministry of Finance and National Economy and the United States Department of State, the Geological Survey and the Arabian American Oil Company prepared these maps which represent the first publicly available documentary results of a program that has been in effect for approximately eight years. The maps resulting from this program are unique in many respects. The large-scale topographic and geologic maps have been published in bilingual Arabic and English editions, while the map of the entire peninsula is printed in English.

The Revue de Geographie Physique et de Geologie Dynamique, Deuxieme Serie, which was published without interruption from 1928 to 1939, resumed publication

in a larger size in July, 1957, under the direction of LEON LUTAUD, JAQUES BOURCART and LOUIS GLANGEAUD.

HANS SCHNEIDERHOHN, Professor of Freiburg University in Briesgau, reached his 70th birthday last June. For this occasion A. CISSARZ and H. BORCHERT each published a brief article in Neues Jahrbuch recounting his many accomplishments and listing his bibliography of 148 articles.

The WYOMING GEOLOGICAL ASSOCIATION held its Thirteenth Annual Field Conference Wednesday morning through Saturday noon, July 23, 24, 25, 26, 1958, at the northwest and east flanks of the Powder River Basin, an area bounded by the Hartville Uplift, the Black Hills Uplift and the Big Horn Mountains.

Three mining engineers of the Paul Weir Co., Chicago, Ill., have returned from South Vietnam where they made a survey of coal resources. DR. CLAYTON G. BALL, President, and D. J. KACHIK and PAUL EYRICH, Senior Engineers, spent three months in the field with headquarters near Tourane, just south of the border separating South Vietnam from its Communist counterpart. They are preparing an economic and engineering report for the International Cooperation Administration on the feasibility of developing coal deposits in the country.

FRANCIS L. PIERSON of United States Potash Company at Carlsbad, N. M., has been promoted from the post of senior geologist to that of chief geologist for the company.

JAMES B. SCOTT, former resident geologist with the Santa Barbara unit of Cia. Minera Asarco, S. A. at Santa Barbara, Chihuahua, Mexico, has returned to the United States and is now living in Oakland, Calif.

RUSSELL GIBSON has accepted a year's assignment with the United Nations Technical Assistance Administration in Pakistan where he will undertake a preliminary survey of that country's radioactive resources and will advise Pakistan's Atomic Energy Commission on a comprehensive program for an atomic raw materials ground survey in both East and West Pakistan. Mr. Gibson was formerly associate professor of economic geology at Harvard University.

R. MASSEY WILLIAMS has resigned as chief consultant on mining engineering and geology for Continental Mining Exploration Ltd., Toronto, Canada, and has returned to private practice as a consultant at 100 Adelaide St. W., Toronto.

THE NINTH ANNUAL FIELD CONFERENCE sponsored by The New Mexico Geological Society with the cooperation of the Arizona Geological Society will take place in the Black Mesa Basin of northeastern Arizona, October 16, 17, 18, 1958. Registration and caravan organization will be at Gallup, New Mexico, on October 15. The conference will deal with the general geology, stratigraphy, structure, economic geology, and water resources of the Black Mesa basin.

CHARLES W. PEGG resigned from Rio Canadian Exploration Ltd. in April to accept a position with the Karl J. Springer interests in Toronto.

WILLIAM B. HEROY, geologist and president, Geotechnical Corp., Dallas, Texas, received a Doctor of Science degree at Syracuse University's 104th Commencement on June 2.

THE DEPARTMENT OF THE INTERIOR on June 13 announced a bid call for constructing new research facilities for the Bureau of Mines at Fort Snelling, Minn., on the Mississippi River adjacent to Minneapolis and St. Paul. Congress has appropriated $1,719,000 for the new laboratory, which will provide space needed by the Bureau for expanding its mining and metallurgical studies on manganese, iron, nickel-copper-cobalt ores, and many other mineral resources of the North Central States.

THE ATOMIC ENERGY COMMISSION announced a revised plan for the commercial distribution of boron-10 materials. Because of its neutron-absorbing qualities, boron-10 is useful in nuclear reactor shielding and control, and in radiation detection instruments. Boron, enriched up to 92 percent in the isotope B-10, will be distributed by the Commission's Chicago Operations Office. While material assaying 92 percent B-10 comprises the major portion of the enriched inventory, there are available smaller quantities of material at certain lower assays. The enriched boron to be distributed is in the form of elemental boron and the compound potassium fluoborate. Storage, packaging and shipping of these materials will be performed by the Michigan Chemical Corp., St. Louis, Michigan.

DAVID D. BAKER has been appointed director of the Production Evaluation Division of the Grand Junction, Colo., office of the U. S. Atomic Energy Commission.

ALBERT A. LEWIS, formerly associated with the Aluminum Co. of America and now practicing consulting geology and mining engineering, has moved his office to 3303 Empty Saddle Road, Rolling Hills, Calif.

CLYDE E. WEED, formerly president, was elected chairman of the board and chief executive officer of Anaconda Co., Chile Copper Co., Chile Exploration Co. and Andes Copper Mining Co., succeeding the late Roy H. Glover.

HENRY K. MARTIN has been appointed to the newly created post of director of mineral development, Oglebay Norton Co.

H. R. COOKE, JR., geologist and engineer of Reno., Nev., is now with Arnold H. Miller Inc., consulting engineer, of New York, in Costa Rica and Cuba.

WILLIAM E. BERTHOLF, II, has been appointed economic geologist on the staff of the State Bureau of Mines and Mineral Resources, a division of the New Mexico Institute of Mining and Technology, Socorro, N. M.

WALLACE A. O'BRIEN, a member of the geological department of The Anaconda Co., has been promoted to mines geologist, succeeding CHARLES C. GODDARD, JR., who has been advanced to geologist in charge of the Company's Butte, Mont., mines.

DR. and MRS. B. S. BUTLER of Tucson have presented $15,000 to the University of Arizona to set up a scholarship fund for graduate work in geology. Dr. Butler was head of the University's department of geology from 1931 to 1948.

ADVERTISEMENTS

Patrons of this journal are requested to refer to ECONOMIC GEOLOGY AND THE BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS when consulting advertisers.

RHOANGLO MINE SERVICES LIMITED

requires a

MINERALOGIST

for employment, under the direction of a senior mineralogist, in a modern research laboratory in Northern Rhodesia specialising in problems covering a wide field in the extractive metallurgy of base metals. Applicants (male or female) must have experience and interest in determinative mineralogy. Basic starting salary dependent on qualifications and experience with minimum of £1,144 per annum plus variable cost of living allowance (at present £68. 0s. 0d. per annum) and a bonus varying with the prosperity of the industry (at present between 10% and 15% of basic salary). Leave 41 to 48 days per annum, accumulative up to 3 years. Generous pension, life assurance, and medical schemes. Accommodation provided at nominal rental. Replies, stating age, marital status, qualifications, experience record and availability, together with names of two referees, and a recent photograph, should be addressed by airmail to:

The Secretaries,
P.O. Box 172,
Kitwe, Northern Rhodesia.

FIFTIETH ANNIVERSARY VOLUME

ECONOMIC GEOLOGY

1905–1955

CONTENTS

Part I

FOREWORD ii
ECONOMIC GEOLOGY ..... *Alan M. Bateman* 1
METALLOGENETIC PROVINCES AND EPOCHS ..... *F. S. Turneaure* 38
THERMAL SPRINGS AND EPITHERMAL ORE DEPOSITS ..... *Donald E. White* 99
THE CLASSIFICATION OF ORE DEPOSITS ..... *James A. Noble* 155
STRUCTURE OF HYDROTHERMAL ORE DEPOSITS ..... *H. E. McKinstry* 170
THE ZONAL THEORY OF ORE DEPOSITS ..... *Charles F. Park, Jr.* 226
TEMPERATURES IN AND NEAR INTRUSIONS ..... *T. S. Lovering* 249
SYNTHETIC MINERALS ..... *W. A. Weyl* 282
HYDROTHERMAL ALTERATION AS A GUIDE TO ORE ..... *George M. Schwartz* 300
OXIDATION OF COPPER SULFIDES AND SECONDARY SULFIDE ENRICHMENT ..... *Charles A. Anderson* 324
METHODS AND PROBLEMS OF GEOLOGIC THERMOMETRY ..... *Earl Ingerson* 341
SEDIMENTARY DEPOSITS OF RARE METALS ..... *Konrad B. Krauskopf* 411
ORIGIN OF URANIUM DEPOSITS ..... *V. E. McKelvey, D. L. Everhart and R. M. Garrels* 464

Part II

ENGINEERING GEOLOGY—A FIFTY YEAR REVIEW ..... *Robert F. Legget* 534
INFLUENCE OF GEOLOGICAL FACTORS ON THE ENGINEERING PROPERTIES OF SEDIMENTS ..... *Karl Terzaghi* 557
RECENT DEVELOPMENTS IN CLAY MINERALOGY AND TECHNOLOGY ..... *Ralph E. Grim* 619
PROPERTIES OF CALCIUM AND MAGNESIUM CARBONATES AND THEIR BEARING ON SOME USES OF CARBONATE ROCKS ..... *D. L. Graf and J. E. Lamar* 639
THE QUANTITATIVE APPROACH TO GROUND-WATER INVESTIGATIONS ..... *John G. Ferris and A. Nelson Sayre* 714
TIME OF PETROLEUM ACCUMULATION ..... *A. I. Levorsen* 748
COAL PETROLOGY ..... *C. E. Marshall* 757
THE USE OF GAMMA RAY MEASUREMENTS IN PROSPECTING ..... *William L. Russell* 835
ECONOMIC APPLICATIONS OF PALEOCOLOGY ..... *Samuel P. Ellison* 867
GEOPHYSICS APPLIED TO PROSPECTING FOR ORES ..... *Louis B. Slichter* 885
MINOR ELEMENTS IN SOME SULFIDE MINERALS ..... *Michael Fleischer* 970
THE STUDY OF PEGMATITE DEPOSITS ..... *Richard H. Jahns* 1025–1130

See order blank in fore-part of this issue.

ECONOMIC GEOLOGY PUBLISHING COMPANY

105 Natural Resources Building, Urbana, Illinois

Price to Subscribers (including members, non-member Journal subscribers, and students whether subscribers or not) $6.00

Price to Non-Subscribers to Journal 8.00

A COMPLETE PRINTING SERVICE

GOOD PRINTING does not just happen; it is the result of careful planning. The knowledge of our craftsmen, who for many years have been handling details of composition, proofreading, presswork and binding, is at your disposal. For seventy-five years we have been printers of scientific and technical journals, books, theses, dissertations and works in foreign languages. Consult us about your next printing job.

• PRINTERS OF • ECONOMIC GEOLOGY

LANCASTER PRESS, Inc.

PRINTERS • BINDERS • ELECTROTYPERS

ESTABLISHED 1877 LANCASTER, PA.

Announcing
SPECIAL STUDENT SUBSCRIPTION RATES

ECONOMIC GEOLOGY

and the Bulletin of the Society of Economic Geologists:

An international journal devoted to the field of Economic Geology

Edited by ALAN M. BATEMAN

Business Editor, MORRIS M. LEIGHTON

8 issues per year

Regular subscription rate, $6.50, student rate, $4.00

(Canadian postage, 30¢)

Students registered in geology courses in the United States and Canada may send for application blank to: Economic Geology Publishing Company, 105 Natural Resources Building, Urbana, Illinois.

A MAJOR ADVANCE!

A TRULY PORTABLE MAGNETOMETER

FOR GEOLOGICAL AND GEOPHYSICAL EXPLORATION

THE VARIAN M-49

operating on revolutionary nuclear-free-precession principle detects variations in the earth's magnetic field associated with magnetic ore bodies, subsurface faults and structural anomalies. Sensitivity of plus or minus 10 gammas is more than ample for the purpose. An extremely short (6 second) automatic reading interval permits rapid reconnaissance of large areas. Weight is only 16 pounds.

The Varian M-49 needs no leveling, calibration or orientation in azimuth. Its readings are precise even when the magnetometer is in motion — carried by a man on foot — mounted on horseback — or embarked in a boat. The sensing head is connected by cable and can be separated from the instrument body by several hundred feet — suspended by balloon — lowered over vertical cliffs.

To achieve these unique properties, Varian uses the proton free-precession principle which relies on an immutable nuclear constant (of the hydrogen atom). Other Varian magnetometers operating on this same principle are in use in magnetic observatories, airborne surveys, underwater surveys and in space vehicles.

FEATURES...

- Range 19,000 to 100,000 gammas.
- Direct reading meter in gammas; sensitivity of ± 10 gammas; no calibration required.
- Weighs only 16 pounds; all-transistor design; compact and rugged.
- Reading interval manually controlled or six-second automatic; usable stationary or in motion.
- Cable-connected sensing head separable by several hundred feet for multilevel surveys.
- Polarizing cells rechargeable by simple connection to automobile battery.

Write today for a full explanation of the Varian Magnetometer's principles, applications and equipment details.

VARIAN associates
INSTRUMENT DIVISION

611 Hansen Way, Palo Alto 14, California

AVAILABLE—ORDER NOW!

ECONOMIC GEOLOGY JOURNAL
INDEX TO VOLS. XLI-L
(1946 - 1955)

Price $3.00

ORDER FORM

To: Economic Geology Publishing Company
105 Natural Resources Building
Urbana, Illinois

Please enter my order for ..... copies @ $3.00 each

Payment ..... enclosed

Please bill me .....

Send copy to: .....

.....

.....

Leitz **first in precision optics**

NEW
POLARIZING
MICROSCOPE SM-pol

Leitz sets a new standard with this student polarizing and chemical microscope of modern design, with dual, low-position focusing controls and large field of view. A reasonably priced polarizing microscope, the model SM-pol, has rugged, one-piece construction with Bertrand lens and pinhole diaphragm built into the tube. Inclined monocular tube will accommodate wide-field eyepieces and the microscope can be used faced away from the observer, permitting easy accessibility to the stage.

A reputation for integrity and a tradition of service have led thousands of scientific workers to bring their optical problems to Leitz. If you have problems in this field, why not let us help you with them?

See your Leitz dealer and examine these Leitz instruments soon. Write for information.

E. LEITZ, INC., Dept. G-8
468 Fourth Avenue, New York 16, N. Y.

Please send me the Leitz _____ brochure.

NAME _____

STREET _____

CITY _____ ZONE _____ STATE _____

E. LEITZ, INC., 468 FOURTH AVENUE, NEW YORK 16, N. Y.
Distributors of the world-famous products of Ernst Leitz G. m. b. H., Wetzlar, Germany—Ernst Leitz Canada Ltd.
LEICA CAMERAS · LENSES · MICROSCOPES · BINOCULARS

ECONOMIC GEOLOGY ISSUES CONTAINING ARTICLES ON URANIUM

Individual numbers of Vols. 46, 50, 51, and 52 are $3.25 per number; for the current Vol. 53, $1.25 per number

VOL. 50, NO. 2. **URANIUM ISSUE** (12 articles on uranium)

VOL. 46, NO. 4. WILLIAM L. RUSSELL and S. A. SCHERBATSKOY: **The Use of Sensitive Gamma Ray Detectors in Prospecting**

VOL. 51, NO. 1. ROGER Y. ANDERSON and EDWIN B. KURTZ, JR.: **A Method for the Determination of Alpha-Radioactivity in Plants as a Tool for Uranium Prospecting.**

VOL. 51, NO. 2. PAUL B. BARTON, JR.: **Fixation of Uranium in the Oxidized Base Metal Ores of the Goodsprings District, Clark Co., Nevada.**

VOL. 51, NO. 3. GEORGE W. WALKER and FRANK W. OSTERWALD: **Uraniferous Magnetite-Hematite Deposit at the Prince Mine, Lincoln County, New Mexico.**

VOL. 51, NO. 4. J. RADE: **Notes on the Geotectonics and Uranium Mineralization in the Northern Part of the Northern Territory, Australia.**

GEORGE E. BOCRAFT: **Uranium Deposits of the Northern Part of the Boulder Batholith, Montana.**

VOL. 51, NO. 6. JOHN W. GRUNER: **Concentration of Uranium in Sediments by Multiple Migration-Accretion.**

R. S. MATHESON and R. A. SEARL: **Mary Kathleen Uranium Deposit, Mount Isa-Cloncurry District, Queensland, Australia.**

VOL. 51, NO. 7. EUGENE B. GROSS: **Mineralogy and Paragenesis of the Uranium Ore, Mi Vida Mine, San Juan County, Utah.**

VOL. 51, NO. 8. PAUL K. SIMS: **Paragenesis and Structure of Pitchblende-bearing Veins, Central City District, Gilpin County, Colorado.**

VOL. 52, NO. 1. ROBERT G. COLEMAN: **Mineralogical Evidence on the Temperature of Formation of the Colorado Plateau Uranium Deposits.**

TOMMY L. FINNELL: **Structural Control of Uranium Ore at the Monument No. 2 Mine, Apache County, Arizona.**

H. D. WRIGHT and D. O. EMERSON: **Distribution of Secondary Uranium Minerals in the W. Wilson Deposit, Boulder Batholith, Montana.**

D. W. BISHOP: **Notes on the Geotectonics and Uranium Mineralization in the Northern Part of the Northern Territory, Australia (Discussions).**

VOL. 52, NO. 2. H. D. WRIGHT and W. P. SHULFOF: **Mineralogy of the Lone Eagle Uranium-Bearing Mine in the Boulder Batholith, Montana.**

L. J. LAWRENCE: **Davidites from the Mt. Isa-Cloncurry District, Queensland.**

GEORGE W. BAIN: **Discussion of Urano-Organic Ores (Discussion).**

VOL. 52, NO. 3. FRANK C. ARMSTRONG: **Eastern and Central Montana as a Possible Source Area of Uranium.**

J. RADE: **Shearing Along Anticlines as an Important Structural Feature in Uranium Mineralization in the Northern Part of the Northern Territory of Australia.**

P. RAMDOHR: **Uraniferous Magnetite-Hematite Deposit at the Prince Mine, Lincoln County, N. M. (Discussion).**

VOL. 52, NO. 6. R. C. VICKERS: **Alteration of Sandstone as a Guide to Uranium Deposits and Their Origin, Northern Black Hills, South Dakota.**

CHARLES F. DAVIDSON: **On the Occurrence of Uranium in Ancient Conglomerates.**

VOL. 52, NO. 7. E. H. GOLDSTEIN: **Geology of the Dakota Formation Uraninite Deposit near Morrison, Colorado.**

VOL. 52, NO. 8. DONALD TOWSE: **Uranium Deposits in Western North Dakota and Eastern Montana.**

VOL. 53, NO. 2. H. D. HOLLAND, G. G. WITTER, JR., W. B. HEAD, III, and R. W. PETTI: **The Use of Leachable Uranium in Geochemical Prospecting on the Colorado Plateau. II The Distribution of Leachable Uranium in Surface Samples in the Vicinity of Ore Bodies.**

VOL. 53, NO. 3. A. VOLBORTH: **Identification Tables for Uranium and Thorium Minerals.**

J. J. BRUMMER: **Supergene Copper-Uranium Deposits in Northern Nova Scotia.**

VOL. 53, NO. 4. J. D. BATEMAN: **Uranium-Bearing Auriferous Reefs at Jacobina, Brazil.**

G. A. SCHNELLMANN: **On the Occurrence of Uranium in Ancient Conglomerates.**

C. J. SULLIVAN: **Ore Genesis—The Source Bed Concept.**

VOL. 53, NO. 5. LEO J. MILLER: **The Chemical Environment of Pitchblende.**

J. J. FRANKEL: **Manganese Ores from the Kuruman District Cape Province, South Africa.**

PAUL RAMDOHR: **On the Occurrence of Uranium in Ancient Conglomerates.**

J. A. S. ADAMS and RICHARD PLILER: **On the Occurrence of Uranium in Ancient Conglomerates.**

Order from: **ECONOMIC GEOLOGY PUBLISHING COMPANY**

105 Natural Resources Bldg., Urbana, Illinois

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

BULLETIN GÉODÉSIQUE

BEING

THE JOURNAL OF

THE INTERNATIONAL ASSOCIATION of GEODESY

★ ★ ★

The scientific articles appearing in this quarterly journal are prepared by the foremost geodesists and geophysicists in the world and deal with the following subjects: Mathematical geodesy (instruments, observations, calculation and adjustment of triangulation); astronomical determination of geographic positions; dynamic geodesy (gravimetry, figure of the Earth, earth tides, isostasy, etc.); leveling. It also contains a section of book notices.

Quarterly *1 volume per year $6.00 (£2.0.0) per volume*

Published by

PERGAMON PRESS

NEW YORK LONDON PARIS LOS ANGELES

122 East 55th Street, New York 22, N.Y. 4 & 5, Fitzroy Square, London W.1.

d. m. organist

PETROGRAPHIC LABORATORY

BOX 176 • NEWARK, DELAWARE

THIN SECTIONS OF

ROCKS, MINERALS, ORES, CERAMICS

PREPARED ROCK SECTIONS FOR STUDENT USE

GRAIN COUNTS • PETROGRAPHIC ANALYSIS

ANNOTATED BIBLIOGRAPHIES OF ECONOMIC GEOLOGY

Available—Vols. I–XXIX, No. 1 (1928–1956).

Vol. XXX (1957) current volume for 1958.

Price $5.00 per volume anywhere in the world thru Volume 27.
Effective Volume 28—price change to $6 per volume.

General Index, Vols. I–XXV, in preparation.

Order now from

ECONOMIC GEOLOGY PUBLISHING COMPANY

105 Natural Resources Building Urbana, Illinois

ECONOMIC GEOLOGY JOURNAL INDEX to Vols. XXXI–XL (1936–1945)—published September, 1947
Price $2.00

Also available Index to Vols. I–XX (1906–1926) —$3.00
Index to Vols. XXI–XXX (1927–1935)— 2.00
Index to Vols. XXXI–XL (1936–1945)— 2.00
Index to Vols. XLI–L (1946–1955) — 3.00

ECONOMIC GEOLOGY PUBLISHING COMPANY

105 Natural Resources Building Urbana, Illinois

FOR SALE

BACK VOLUMES OF ECONOMIC GEOLOGY

From Stock:

Complete Volumes: 3, 6, 7, 8, 9, 10, 11, 15, 22, 25 @ $15 per volume

Complete Volumes: 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50 @ $12 per volume

Incomplete Volumes but from which certain issues are still available (some of them almost complete):
1, 2, 4, 5, 12, 13, 14, 16, 17, 18, 19, 21, 23, 24 @ $2.25 per issue

Also shelf worn copies of scattered numbers thruout the series @ 75¢ per copy

Inquire:

Economic Geology Publishing Company
105 Natural Resources Building
Urbana, Illinois

Special Price—

A. A. P. G. COMPREHENSIVE INDEXES, 1917—1955

Encompass all A.A.P.G.'s Bulletins and special publications for a 38-year period. A valuable addition to the geologist's library. Cloth bound.

BOTH INDEXES	member price, $5.00; others, $7.00		
SINGLY	1917–45, one volume	3.00	4.00
	1946–55, one volume	3.00	4.00

ORDER FROM

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

Box 979, Tulsa 1, Oklahoma, U. S. A.

LABORATORY FOR ROCK ANALYSIS

Chemical analyses of rocks and minerals made with accuracy required for research. Commercial work cannot be accepted.

SAMUEL S. GOLDICH, in charge

Department of Geology and Mineralogy, University of Minnesota, Minneapolis 14, Minnesota

---

ROCK THIN SECTIONS

•

MOUNTED ORE SECTIONS

Fred Roberts » » »

PETROGRAPHIC SECTION SERVICE

2636½ W. MAIN ST., ALHAMBRA, CALIFORNIA

SWAN ENGRAVING COMPANY

PHOTO ENGRAVERS COMMERCIAL ARTISTS

BRIDGEPORT, CONN. NEW HAVEN, CONN

POUGHKEEPSIE, N.Y.

Geophysics for Economic Geologists

GEOPHYSICAL CASE HISTORIES, VOLUME I (1948) $7.00
GEOPHYSICAL CASE HISTORIES, VOLUME II (1956) $7.00
CUMULATIVE INDEX, 1931–1953 (All publications) $4.00
GEOPHYSICS (Quarterly) Per year $10.00

Detailed list of publications on request

Send Order with Remittance to
SOCIETY OF EXPLORATION GEOPHYSICISTS
Box 1536 Tulsa 1, Oklahoma

PROBLEMS OF PETROLEUM GEOLOGY

Sidney Powers Memorial Volume

A Sequel to *Structure of Typical American Oil Fields*

A compilation of 43 papers prepared for this volume by 47 authors

1,073 pp., 200 illus. Cloth. Price, postpaid: to members, $4.00; to non-members, $5.00. Usual discounts to educational institutions.

The American Association of Petroleum Geologists
Box 979 . . . Tulsa 1, Oklahoma

FRANTZ ISODYNAMIC Magnetic SEPARATOR

NOW made with BUILT-IN RECTIFIER for LOWER COST to you

We are now incorporating a silicon rectifier inside the base of the ISODYNAMIC SEPARATOR, replacing the external rectifier formerly required at extra cost. This has been done without increasing the price of the separator and is equivalent to a 7% price reduction for the complete outfit. The controls for the magnet and vibrator, as well as the rectifier, are now all contained in the base of the separator.

VERTICAL FEED

INCLINED FEED

The ISODYNAMIC Magnetic Separator is in world-wide use as a most valuable research tool for the mineral investigator. It is highly selective—able to discriminate between the most feebly magnetic minerals, even when their susceptibilities are extremely close together. This is due to the special shape of the pole pieces which produces a magnetic field in which a uniform force is exerted on a particle of given susceptibility anywhere in the operating space.

For Complete Information— Write for BULLETIN 132-I

S. G. FRANTZ Co., Inc.

E N G I N E E R S

P.O. Box 1138
Trenton 6, New Jersey, U.S.A.

Cable Address:
MAGSEP, Trentonnewjersey

BOOKS IN GEOLOGICAL SCIENCE

Address ECONOMIC GEOLOGY, Urbana, Ill. Books not in this list (except the publications of official Surveys and those of the Geological Society of America) will be furnished at Publishers' prices.

AREAL GEOLOGY AND REGIONAL

Guidebook to the Geology of North and Middle Parks Basin, Colorado. By ROCKY MOUNTAIN ASSOCIATION OF GEOLOGISTS. WILLIAM C. FINCH, Editor. 1957. Pp. 152 ..... 8.50

Guide to the Geology of Central Colorado. By JOHN W. VANDERWILT and others. 1948. Pp. 176.. $ 3.00

Geology of the Golden-Green Mountain Area, Jefferson County, Colorado. By STANLEY O. REICHERT. 1953. Pp. 96. 19 halftone photographs and a folder of detailed maps and tables 1.50

Geological Survey of Great Britain. By EDWARD B. BAILEY. 1952. Pp. 278. Pls. 4. Figs. 39... 4.00

The Geology of the Commonwealth of Australia. By T. W. E. DAVID. 1950. Three volumes..... 50.00

I. Historical Geology. Pp. 720. Pl. 57. Figs. 208.
II. Physiography. Pp. 645. Pl. 28. Figs. 164.
III. Maps: Geological Map of the Commonwealth of Australia (11 sections on 4 sheets), and **Geological Sketch-Map of Australian New Guinea** (1 section).

Late Cenozoic Erosional History of the Raton Mesa Region. By WILLIAM S. LEVINGS. 1951. Pp. 111. Illus. 31. 16 large contour and cross-section maps 2.50

Historical Geology of the Antillean-Caribbean Region. By CHARLES SCHUCHERT. 1935. Pp. 811. Illus. 6 x 9¼ 15.00

Los Yacimientos Minerales de Bolivia. By FEDERICO AHLFELD. 1954. Pp. 277 ..... 6.00

Structural History of the East Indies. By J. H. F. UMBGROVE. 1949. Pp. 63. Figs. 68 ..... 8.50

The Geology of Indonesia. By R. W. VAN BEMMELEN. 1949.
Vol. I: General Geology of Indonesia and Adjacent Archipelagos. Pp. 732. Tables 124.
Vol. II: Economic Geology of Indonesia. Pp. 265. With 52 figures and 56 tables.
Price of the two volumes and portfolio. Cloth ..... 75 Guilders

Geology of India. 3rd Ed. By D. N. WADIA. 1953. Pp. 552. Pl. 18. 6 maps, 25 x 30 full color geological map of India 10.00

COSMOGONY

Astrophysics. By LAWRENCE H. ALLER. 1953.
Vol. 1. The Atmospheres of the Sun and Stars. Pp. 412. Figs. 118 ..... 12.00
Vol. 2. Nuclear Transformations, Stellar Interiors, and Nebulae. Pp. 291. Figs. 51 ..... 12.00

The Changing Universe. By JOHN PFEIFFER. 1956. Pp. 243. Illus 4.75

Expanding Universes. By E. SCHRODINGER. 1956. Pp. 93. Illus. 10 ..... 3.50

The Physical World. By PAUL MCCORKIE. 1956. Pp. 465 ..... 5.25

The World We Live In. By LINCOLN BARNETT and editorial staff of Life. 1955. Pp. 304. Illus... 13.50
deluxe 15.50

The Radiant Universe. By GEORGE W. HILL. 1953. Pp. 489 ..... 4.75

The Earth as a Planet. GERARD P. KUIPER, Editor. 1954.
Vol. II of the Solar System. Pp. 751 ..... 12.50

Astronomy of Stellar Energy and Decay. By MARTIN JOHNSON. 1951. Pp. 216. Figs. 22 ..... 3.50

CRYSTALLOGRAPHY AND MINERALOGY

Elementary Crystallography. By M. J. BUERGER. 1956. Pp. 528 ..... 8.75

An Introduction to Crystallography. By F. C. PHILIPS. 2nd Edition. P. viii + 324; Figs. 515..... 6.00

Laboratory Manual of Crystallography for Students of Mineralogy and Geology. By GEORGE TUNELL and JOSEPH MURDOCK. 1957. Pp. 55, Figs. 20 ..... 2.75

Crystal Data, a classification of substances by space groups and their identification from cell dimensions. 1954. Memoir 60. Pp. 719. Figs. 4 ..... 5.00

Crystal Growth. By H. E. BUCKLEY. 1951. Pp. 571 ..... 10.00

Crystals and the Polarizing Microscope. 2nd Ed. By N. H. HARTSHORNE and A. STUART. 1950. Pp. 473. Diags. 313 ..... 12.50

Optical Crystallography. 2nd Ed. By E. E. WAHLSTROM. 1951. Pp. 206. Figs. 209 ..... 5.00

X-Rays in Practice. By W. T. SPROULL. 1946. Pp. 603. Illus 8.00

Crystal Structures. Volume I. By RALPH W. G. WYCKOFF. 1948. Pp. 256. Illus. 66. 122 pages of tables. Loose-leaf with binder 8.00

Supplement Volume I: 1951. 72 text pages. 64 pages of tables 4.00

Crystal Structures. Volume II. 1951. By RALPH W. G. WYCKOFF. 253 text pages, 74 illus. 256 pages of tables. With binder 10.00

Supplement II: 1953. 30 Pp. 64 tables 4.00

Crystal Structures. Volume III. 1953. By RALPH W. G. WYCKOFF. 244 Pp., 176 Illus. 220 tables 14.50

Supplement III: 1958. Pp. 547. Tbls. 142. Illus. 234 ..... 20.00

Crystal Structures: Vol. IV. 1957. Pp. 206. Tbls. 55 ..... 7.00

The Crystalline State. Edited by W. H. BRAGG.
Vol. 1: A General Survey. New Ed. By L. BRAGG. 1949. Pp. 352. Illus 5.50
Vol. 2: Optical Principles of the Diffraction of X-Rays. By R. W. JAMES. 1949. Pp. 623..... 13.00
Vol. 3: Determination of Crystal Structures. By LIPSON and COCHRAN. 1954. 345 Pp..... 8.00

(Continued on Page xiv)

(*Continued from Page xiii*)

BOOKS IN GEOLOGICAL SCIENCE

CRYSTALLOGRAPHY AND MINERALOGY (Continued)

The Barker Index of Crystals.—A Method for the Identification of Crystalline Substances. By M. W. PORTER and R. C. SPILLER. 1951. Pp. 1500.
Vol. I, Part 1 ..... 6.00
Part 2 ..... 18.00

Phase Microscopy. By A. BENNETT and others. 1951. Pp. 320 ..... 11.00

X-Ray Analysis of Crystals. By J. M. BIJVOET and others. Translated by H. LITTMAN FURTH. 2nd Ed. 1951. Pp. 310. Illus. 8.00

X-ray Crystallography. 4th Ed. By R. W. JAMES. 1950. Pp. 88 ..... 1.75

X-ray Crystallography. By MARTIN J. BUERGER. 1942. Pp. 531. Illus. 252 ..... 9.50

Imperfections in Nearly Perfect Crystals. By W. SHOCKLEY. 1952. Pp. 490; figs. 175 ..... 9.00

Elements of Optical Mineralogy. By ALEXANDER N. WINCHELL.
Pt. I. Principles and Methods. 5th Ed. 1937, Pp. 263. Illus. 305 ..... 5.75
Pt. II. Description of Minerals. 4th Ed. 1951. Pp. 551 ..... 13.50
Pt. III. Determinative Tables. 2nd Ed. 1939. Pp. 244 ..... 7.50

Optical Mineralogy. 2nd Ed. By AUSTIN F. ROGERS and PAUL F. KERR. 1942. Pp. 390. Figs. 369. Cloth 7.00

Tables for Microscopic and X-ray Identification of Ore Minerals. By ALEXANDER NOVITZKY. In Spanish. 1957. Pp. 270 ..... 12.00

Stereograms for the Determination of Plagioclase Feldspars in Random Sections. By W. NIEUWENKAMP. 1948. Pp. 29 ..... 6.40

Mineralogy. 4th Ed. By E. H. KRAUS, W. F. HUNT, and L. S. RAMSDEL. 1951 ..... 8.00

Identification and Qualitative Chemical Analysis of Minerals. By ORSINO C. SMITH. 1953. Pp. 400. Col. Pl. 27. Figs. 22 ..... 8.50

Clay Mineralogy. By RALPH E. GRIM. 1953. Pp. 384. Fig. 121. Tables 46 ..... 9.50

Analysis of Minerals and Ores of the Rarer Elements. By W. R. SCHOELLER and A. R. POWELL. 3rd Ed. Rev. 1956. Pp. 408 ..... 9.75

Dana's System of Mineralogy. By CHARLES PALACHE, HARRY BERMAN and CLIFFORD FRONDEL.
Vol. I. Elements, Sulfides, Sulfosalts, Oxides. 7th Ed. 1944. Pp. 834. Illus. 14.00
Vol. II. Halides, Carbonates, etc. 7th Ed. 1951. Pp. 1124. Illus. 16.00

Manual of Mineralogy. By J. S. DANA—16th Ed. Revised by C. S. HURLBUT. 1952. Pp. 539 ..... 7.00

Minerals and How to Study Them. 3rd Ed. By EDWARD S. DANA. Revised by CORNELIUS S. HURLBUT, JR. 1949. Pp. 323. Illus. 384 ..... 5.75

Elements of Mineralogy. 24th Ed. By FRANK RUTLEY (Revised by H. H. READ). 1953. Pp. 535. Illus. 138 ..... 2.50

Textbook of Mineralogy. 13th Rev. Ed. By KLOCKMANN. 1948. Pp. 674. Illus. 606 ..... Stitched 15.94 ..... Bound 16.46

Dana's Textbook of Mineralogy. 4th Ed. Revised by WM. E. FORD. 1932. Pp. 851. Illus., Diagrams 8.00

A Field Guide to Rocks and Minerals. By FREDERICK H. POUGH. 1953. Pp. 331. 12 Color Pls., 32 black and white numerous crystal drawings 3.95

Rutley's Elements of Mineralogy. 25th Ed. By H. H. READ. 1953. Pp. 525, figs. 137 ..... 2.50

Introduction to Study of Minerals and Rocks. 3rd Ed. By AUSTIN L. ROGERS. 1937. Pp. 626. Illus. 7.50

Handbook of Mineralogy, Blowpipe Analysis and Geometrical Crystallography. Combined Ed. By G. MONTAGUE BUTLER. 1918. Pp. 546. 4½ x 7 ..... 6.50

The Colloid Chemistry of the Silicate Minerals. By C. EDMUND MARSHALL. 1953. Pp. 195. Illus. 6.50

Colorimetric Determination of Traces of Metals. By ERNEST B. SANDELL. 1944. 2nd Ed. Revised. Pp. 693. Illus. 83, Tables 107 ..... 10.50

How to Know Minerals and Rocks. By RICHARD M. PEARL. 1955. Pp. 192. Figs., Keys 3.50

Minerals and Rocks. By RUSSELL D. GEORGE. 1943. Pp. 595. Figs. 150. Pls. 48 ..... 6.00

Quartz Family Minerals. By H. C. DAKE, F. L. FLEENER, and B. H. WILSON. 1938. Pp. 304 ..... 4.75

A Handbook of Gem Identification. 5th Rev. Ed. By RICHARD T. LIDDICOAT, JR. 1953. Pp. 349. Illus. 117 ..... 6.00

Jewelry, Gem Cutting, and Metalcraft. 3rd Ed. By WILLIAM T. BAXTER. 1950. Pp. 360. Illus. 175 ..... 4.50

The Art of the Lapidary. By F. J. SPERISEN. 1950. P. 278. Illus. 406 ..... 7.00

Gem Testing. By B. W. ANDERSON. 1948. Pp. 256. Illus. 55 ..... 5.00

Dictionary of Gems and Gemology. 4th Ed. By R. M. SHIPLEY. 1951. Pp. 260 ..... 5.50

A Key to Precious Stones. 2nd Ed. By L. J. SPENCER. 1946. Pp. 237. 57 Illus. 8 pp. pls. 3.50

Gems and Gem Materials. 5th Ed. By EDWARD H. KRAUS and C. B. SLAWSON. 1947. Pp. 332. Illus. 6.00

Colorado Gem Trails. By R. M. PEARL. 3rd Ed. 1953. Pp. 128. Photos; Sketch maps 2.25

Popular Gemology. By RICHARD M. PEARL. 1948. Pp. 316. Figs. 115 ..... 5.50

A Handbook of Precious Stones. By WAO BAHADUR DR. L. A. N. IYER. 1948. Pp. 188. Figs. 39. 3.15

A Roman Book on Precious Stones. By SYDNEY H. BALL. 1950. Pp. 360 ..... 6.75

(*Continued on Page xv*)

(*Continued from Page xiv*)

BOOKS IN GEOLOGICAL SCIENCE

ECONOMIC GEOGRAPHY

Geography in the Twentieth Century. Edited by GRIFFITH TAYLOR. 1951. Pp. 630. Figs. 56.... 10.00

Economic Geography of Industrial Materials. By ALBERT S. CARLSON, Ed. 1956. Pp. 494..... 12.50

The Nation Looks at its Resources. By HENRY JARRET. 1954. Pp. 417..... 5.00

Geography of North America. By GEORGE J. MILLER, ALMON E. PARKINS and BERT HUDGINS. 1954. 3rd Ed. Pp. xi + 664. Figs. 290, tbls. 25..... 7.50

California and the Southwest. Ed. by CLIFFORD M. ZIERER. 1956. Pp. 376: Illus..... 11.25

Mineral Commodities of California. Prepared under direction of OLAF P. KENKINS. Edited by LAUREN A. WRIGHT. 1957. Pp. 736. Figs. 130 Maps and Cross-sections. Photographs. 239.. 7.50

Geography of the Northlands. By GEORGE H. T. KIMBLE and DOROTHY GOOE. 1955. Pp. 534, Illus. 10.00

Industrial and Commercial Geography. 3rd Ed. By J. RUSSELL SMITH and M. O. PHILLIPS. 1946. Pp. 978..... 6.50

Economic Geography: New Edition. By CHARLES C. COLBY and ALICE FOSTER. 1954. Pp. 685... 3.72

World Economic Geography. By EARL B. SHAW. 1955. Pp. 582. Figs. 339. Tables 12..... 6.50

World Commerce and Governments. By W. S. WOYTINSKY and E. S. WOYTINSKY. 1955. Pp. 906. Figs. 166. Tables 291..... 10.00

World Population and Production. By W. S. WOYTINSKY and E. S. WOYTINSKY. 1953. Pp. 1268, tbls. 338, pls. 338..... 12.00

Geography of Living Things. By M. S. ANDERSON. 1952. Pp. 202. Figs. 5..... 2.75

Fundamentals of Economic Geography. 3rd Ed. Rev. Ed. by NELS A. BENGSTON and W. VAN ROYEN. 1950. Pp. 574. Phots. 142. Maps 76. Charts, etc. 150..... 7.90

Economic and Industrial Geography. By A. M. NIELSEN. 1950. Pp. 728..... 6.75

Principles of Economic Geography. By ELLSWORTH HUNTINGTON assisted by FRANK E. WILLIAMS, SAMUEL VAN VALKENBERG, and STEPHEN S. VISHER. 1940. Pp. 715. Illus..... 6.00

Physical Elements of Geography. 3rd Ed. By V. C. FINCH and G. T. TREWARTHA. 1949. Pp. 696. Illus..... 6.25

Advanced Atlas of Modern Geography. By JOHN BARTHOLOMEW. 1950. Pp. 155, 108 of which are maps. Printed in Great Britain at the Geographical Institute..... 9.50

Principles of Human Geography. Rev. Ed. By ELLSWORTH HUNTINGTON and EARL B. SHAW. 1951. Pp. 805. Illus. including black and white maps..... 6.75

Europe. 2nd Ed. By PROF. VAN VALKENBURG and COLBERT C. HELD. 1952. Pp. 826..... 7.50

Friendly China. By BAILEY WILLIS. 1949. Pp. 312. Numerous sketches..... 5.00

Southeast Asia. By E. G. H. DOBBY. 1950. Pp. 415..... 5.00

Asia, East by South. By J. E. SPENCER. 1954. Pp. 453. Figs. 136..... 8.50

Conserving Natural Resources—Principles and Practice in a Democracy. By SHIRLEY W. ALLEN. 1955. Pp. 347, Figs. 168..... 5.50

Conservation in the United States. 3rd Ed. By AXEL F. GUSTAFSON, C. H. GUISE, W. J. HAMILTON, JR., and H. RIES (Members of the faculty of Cornell University). 1949. Pp. 544. Illus. 254.. 5.00

The Pacific Northwest. By O. W. FREEMAN, H. H. MARTIN, and others. 2nd Ed. 1954. Pp. 542. Illus..... 8.50

The U.S.S.R.—A Geographical Survey. By J. S. GREGORY and D. W. SHAVE. 1946. Pp. 636. Illus. 6.00

ECONOMIC GEOLOGY

The Formation of Mineral Deposits. By ALAN M. BATEMAN. 1951. Pp. 334. Illus..... 6.25

Mining Geology. By HUGH E. MCKINSTRY. 1948. Pp. 680..... 8.50

Principles of Field and Mining Geology. By J. DONALD FORRESTER. 1946. Pp. 647. Illus. 316... 8.75

Economic Mineral Deposits. 2nd Ed. By ALAN M. BATEMAN. 1950. Pp. 918. Illus. 308..... 8.75

Textures of the Ore Minerals and their Significance. By A. B. EDWARDS. 2nd Ed. 1954. Pp. 242. 204 Illus..... 14.00

Flotation. By A. M. GAUDIN. 1957. Pp. 573 ..... 12.50

Non-Metallic Minerals. 2nd Ed. By RAYMOND B. LADOO and W. M. MYERS. 1951. Pp. 605.... 11.00

Minerals and Mineral Deposits. By W. R. JONES and D. WILLIAMS. 1948. Pp. 255. Figs. 36. Maps. Bibliography. Tables..... 1.20

Mineral Deposits. 4th revised Ed. By WALDEMAR LINDGREN. 1953. Pp. 930..... 11.00

Minerals for Atomic Energy. 2nd Ed. By ROBERT D. NININGER. 1956. Pp. 399, Illus..... 8.50

Ore Genesis. By J. S. BROWN. 1948. Pp. 204. Illus. 4..... 3.50

Ore Deposits as Related to Structural Features. Edited by WALTER H. NEWHOUSE. 1942. Pp. 292. Illus. 250. Cloth, 9 x 12..... 8.50

The Origin and Nature of Ore Deposits. By R. T. WALKER and W. J. WALKER. 1956. Pp. 384... .....United States 6.50
Other Countries 7.00
Canada & Mexico 6.75

Structural Geology of Canadian Ore Deposits (Symposium volume published in commemoration of 50th Anniversary of the Canadian Institute of Mining and Metallurgy). 1951. Pp. 930 (132 separate papers as written by over 100 Canadian mining executives). Illus. 300..... 10.00
Price to qualified students..... 8.00

Exploration for Nuclear Raw Materials. By ROBERT D. NININGER. 1956. Pp. 293..... 8.50

Uranium (Where it is and how to find it). By P. D. PROCTOR, E. P. HYATT, and K. C. BULLOCK. 1954. Pp. 96. 18 full pages maps. Illus.....Cloth 2.50
Paper 2.00

(*Continued on Page xvi*)

(*Continued from Page xv*)

BOOKS IN GEOLOGICAL SCIENCE

ECONOMIC GEOLOGY (Continued)

Minerals, for the Chemical and Allied Industries. By SIDNEY J. JOHNSTONE. 1954. Pp. 692..... 12.50

Copper Venture. By KENNETH BRADLEY. 1952. Pp. 112. Illus. and Maps..... 2.30

Tin 1954: A Review of the World Tin Industry. By INTERNATIONAL TIN STUDY GROUP. 1955. Pp. 56. Charts 23..... 1.00

Cobalt. (ACS Monograph, 108). By ROLAND S. YOUNG. 1948. Pp. 180. Illus..... 5.50

Lazarus Erker's Treatise on Ores and Assaying. By A. G. SISCO and C. S. SMITH. 1952. Pp. 360. Illus. 41..... 10.00

Occurrence and Production of Molybdenum. By J. W. VANDERWILT. 1942. Pp. 78. Paper..... 1.50

Mineral Resources of China. By V. C. JUAN. 1946. Pp. 75. Illus. Paper..... .75

The Coalfields of Great Britain. By SIR ARTHUR TRUEMAN. 1954. Pp. xi + 396, pls. 7, figs. 106, tbls. 5..... 15.00

Coal: Its Formation and Composition. By WILFRED FRANCIS. 1954. Pp. 567..... 22.00

Coals and Bitumens. By S. I. TOMKEIEFF. 1954. Pp. 122. Illus. 4..... 3.00

Progress in Coal Science. Vol. I. By D. H. BANGHAM (ed.). 1950. Pp. 469. Illus. 32. Tables 29, Pl. 12..... 7.00

The Nature and Origin of Coal and Coal Seams. By ARTHUR RAISTRICK and C. E. MARSHALL. 1939. Pp. 312. Figs. 100..... 2.60

Coal Through the Ages. By H. N. EAVENSON. 1939. Pp. 123..... 1.80

Coalmining. By I. C. F. STATHAM. 1951. Pp. 564. Illus..... 15.00

Geology of Petroleum. By A. I. LEVORSEN. 1954. Pp. 720, illus. 327. Tables 47..... 8.00

North American Petroleum. 1957. Rev. Ed. 1952. By W. A. VER WIEBE. Pp. 461. Illus. 396 12.00

Graphic Problems in Petroleum Geology. By L. W. LEROY and JULIAN W. LOW. 1957. Pp. 238. 4.50

Principles of Petroleum Geology. By CECIL G. LALICKER. 1949. Pp. 377. Illus. Pl. Maps.... 5.00

Petroleum Geology. By KENNETH K. LANDES. 1951. Pp. 660. Illus. 241..... 10.00

Principles of Petroleum Geology. By W. L. RUSSELL. 1951. Pp. 508. Figs. 132..... 7.50

Some Fundamentals of Petroleum Geology. By G. D. HOBSON. 1954. Pp. 139. Figs. 41..... 2.90

Basic Oil Geology. By WILLIAM W. PORTER II. 1956. Pp. 142. Figs. 21..... 4.00

How Oil is Found. By W. A. VER WIEBE. 1951. Pp. 247. Illus. 312..... 8.50

Fundamental Research on Occurrence and Recovery of Petroleum, 1950–51. By LLOYD E. ELKINS. 1953. Pp. 263..... 6.00

Principles of Petroleum Geology. By E. N. TIRATSOO. 1951. Pp. 449..... 7.50

Practical Oil Geology. 6th Ed. By DORSEY HAGER. 1951. Pp. 466. 5¼ x 7½. Illus..... 8.00

Fundamentals of Logging. 1957. Pp. 169..... 3.00

Structure of Typical American Oil Fields. Vol. III. 1948. Pp. 516. Illus. 219..... 4.50

Petroleum Microbiology. By ERNEST BEERSTECHER, JR. 1954. Pp. 375; figs. 71..... 8.00

Oil Property Valuation. By PAUL PAINE. 1942. Pp. 204..... 5.50

Properties of Petroleum Reservoir Fluids. By EMIL BURCIK. 1957. Pp. 190..... 7.50

Physical Principles of Oil Production. By MORRIS MUSKAT. 1949. Pp. 922. Illus..... 15.00

Oil and Gas Production. By THE ENGINEERING COMMITTEE OF THE INTERSTATE OIL COMPACT COMMISSION. Pp. 140. Illus. with charts, graphs, and tables..... 2.75

Practical Petroleum Engineers Handbook. 3rd Ed. 1951. Pp. 654. Illus. by JOSEPH ZABA and W. T. DOHERTY..... 11.00

Elements of Petroleum Subsurface Engineering. By HAROLD VANCE. 1950. Pp. 168. Illus. 108.. 4.25

Oil Reservoir Engineering, 2nd Edit. By SYLVAIN J. PIRSON. 1958. Pp. 735..... 14.00

Secondary Recovery of Oil. By OSCAR F. SPENCER. 1949. Pp. 441. Illus. 107..... 4.50

Oil Well Drainage. By S. C. HEROLD. 1941. Pp. 407. Figs. 15..... 5.00

World Geography of Petroleum. Edited by W. E. PRATT and DOROTHY GOOD. 1950. Pp. 482. Illus. 9.00

Early Days of Oil. By P. H. GIDDENS. 1948. Pp. 160. Illus..... 6.00

North American and Middle East Oil Fields. By W. A. VER WIEBE. 1950. Pp. 260. Illus. 110.... 6.00

Oil in the Soviet Union: History, Geography, Problems. By HEINRICH HASSMANN. Translated from the German with the addition of much new information, by ALFRED M. LEESTON. 1953. Pp. 173. Figs. 19 (maps and charts). Tables 43..... 3.75

Petroleum Production Economics. By LESTER CHARLES UREN. 1954. Pp. 614. Illus..... 8.00

Petroleum Production Engineering. By LESTER C. UREN.

Vol. I. Oil Field Development. 1946. Pp. 764..... 9.50

Vol. II. Oil Field Exploitation. 3rd Ed. 1953. Pp. 807. Illus. 367..... 10.00

Vol. III. Petroleum Production Economics. 4th Ed. 1956. Pp. 792. Figs. 117. Tables 74. 12.00

Science and Petroleum. By A. E. DUNSTAN, et al.

Vol. I. 1938. Pp. 836. Illus. Figs.

Vol. II. 1938. Pp. 1669. Illus. Figs.

Vol. III. 1938. Pp. 2385. Illus. Figs.

Vol. IV. 1938. Pp. 3192. Illus. Figs. Available as a set @ $60.00 (Vols. I-IV)

Vol. V. 1950. Pp. 200. Illus. Part I is available separately..... 11.00

Natural Gas and Natural Gasoline. By R. L. HUNTINGTON. 1950. Pp. 598. 6 x 9. Illus. 267.... 10.00

Encyclopedia of Hydrocarbon Compounds. Vol. X. $C_{11}H_8$ to $C_{11}H_{14}$. By JOSEPH E. FARADAY. 1951. Pp. 270..... 15.50

(*Continued on Page xvii*)

(*Continued from Page xvi*)

BOOKS IN GEOLOGICAL SCIENCE

ECONOMIC GEOLOGY (Continued)

Shale Oil (ACS Monograph No. 25). By RALPH H. McKEE and 7 Collaborators. 1925. Pp. 326. Figs. 36. 6 x 9 ..... 2.50

Petroleum Conservation. Edited by STUART E. BUCKLEY. 1951. Pp. 300. Illus. 6.00

The Uranium Prospector's Guide. By THOMAS J. BALLARD and QUENTIN E. CONKLIN. 1955. Pp. 251 ..... 3.50

Exploration for Nuclear Raw Materials. By ROBERT D. NININGER. 1956. Pp. 293 ..... 8.50

Regional Tectonics of the Colorado Plateau and Relationship to the Origin and Distribution of Uranium. By V. C. KELLEY. 1955. Pp. 120. Figs. 17. Pls. 8 ..... 2.00

The Conservation of Ground Water. By HAROLD E. THOMAS. 1951. Pp. 321. Illus. 6.50

Soil and Water Conservation Engineering. By RICHARD K. FREVERT, GLENN O. SCHWAB, TALCOTT W. EDMINSTER and KENNETH K. BARNES. 1955. Pp. 479. Illus. 8.00

Realms of Water. (Some Aspects of Its Cycle in Nature). By P. H. KUENEN. 1955. Pp. 320 .... 6.50

Groundwater. By CYRUS F. TOLMAN. 1937. Pp. 593. Illus. 189 ..... 9.00

The Geology of Water Supply. By CYRIL S. FOX. 1949. Pp. 209. Profusely illustrated. Cloth .. 7.75

Applied Hydrology. By R. K. LINSLEY, JR., MAX A. KOHLER, and J. L. H. PAULHUS. 1949. Pp. 689. Illus. 328 ..... 9.00

Hydrology. By OSCAR E. MEINZER. 1949. Pp. 723. Illus. 165 ..... 4.95

Hydrology. By C. O. WISLER and E. F. BRATER. 1949. Pp. 419. Illus. 7.00

Elements of Applied Hydrology. By D. JOHNSTONE and W. P. CROSS. 1949. Pp. 276. Illus. 109. Tables 32 ..... 5.00

A Practical Handbook of Water Supply. By FRANK DIXEY. 1950. Pp. 573; maps 6; figs. 133 ..... 35s

Water Supply and Waste-Water Disposal. By GORDON MASKEW FAIR and JOHN CHARLES GEYER. With a chapter (on water chemistry) by JOHN CARRELL MORRIS. 1954. Pp. 973. Illus. 15.00

The Flood Control Controversy. By LUNA B. LEOPOLD and THOMAS MADDOCK, JR. 1954. Pp. 278. 5.00

Principles of Engineering Geology and Geotechnics. By D. P. KRYNINE and W. R. JUDD. 1957. Pp. 736 ..... 10.00

Geology in Engineering. By JOHN R. SCHULTZ and ARTHUR B. CLEAVES. 1955. Pp. 592. Illus. 214 ..... 8.75

Geology and Engineering. By ROBT. F. LEGGET. 1939. Pp. 650. Illus. Cloth, 6 x 9 ..... 7.50

Geology for Engineers. By J. M. TREFETHAN. 1949. Pp. 620. Illus. 6.00

Geology for Engineers. 3rd Ed. By FRANCIS G. BLYTH. 1952. Pp. 336. Illus. 4.75

Elements of Engineering Geology. 2nd Ed. Revised (1947). By HEINRICH RIES and T. L. WATSON. Pp. 469. Illus. 293 ..... 7.00

Geology Applied to Building and Engineering. By ARTHUR BRAY. 1948. Pp. 196 ..... 6.25

Heat Conduction, with Engineering, Geological, and Other Applications. By L. R. INGERSOLL, O. J. ZOBEL, and A. C. INGERSOLL. 1954. Pp. 325. Figs. 53 ..... 5.00

Applied Geology, a Symposium. By F. M. VAN TUYL and TRUMAN H. KUHN. Vol. 45, No. 1-B. 1950. Pp. 343 ..... 3.00

Mineral Resources of the United States. By the STAFFS OF THE U. S. BUREAU OF MINES AND THE GEOLOGICAL SURVEY. 1948. Pp. 212 ..... 5.00

The Chemistry of Portland Cement. 2nd Ed. By ROBERT HERMAN BOGUE. 1955. Pp. 793. Illus. 16.50

Refractories. 3rd Ed. By F. H. NORTON, 1949. 782 Pp. 419 Illus. 11.00

Microscopy of Ceramics and Cements. Including glasses, slags, and foundry sands. By HERBERT INSLEY and VAN DERCK FRÉCHETTE. 1955. Pp. 286. Illus. 7.50

The Vermiculites and Their Utilization. By AUGUST GOLDSTEIN, JR. 1946. Pp. 64 ..... 1.00

The Occurrence and Production of Vanadium. By G. O. ARGALL, JR. 1943. Pp. 56 ..... 1.00

Foundation Engineering. By PECK, HANSON, and THORNBURN. 1953. Pp. 410 ..... 8.00

Landslides and Engineering Practice HRB Special Report 29. Edited by EDWIN B. ECKEL, Chairman. Prepared by the Committee on Landslide Investigations. 126 Illus. 6 tables. 1 plate. Pp. 232 6.00

Soil Mechanics in Engineering Practice. By KARL TERZAGHI and RALPH B. PECK. 1948. Pp. 566. 7.00

Soil Mechanics. 2nd Ed. By D. P. KRYNINE. 1947. Pp. 450. Illus. 7.50

Fundamentals of Soil Mechanics. By DONALD W. TAYLOR. 1948. Pp. 700. Illus. 239 ..... 7.50

Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes. By M. JUUL HVORSLEV. 1949. Pp. 521. Illus. 450 ..... 6.00

Introduction to Mine Surveying. By W. W. STALEY. 1939. Pp. 275. Illus. 3.75

A Mining Engineer's Survey Manual. By J. E. METCALFE. 1951. Pp. 341 ..... 30s

Mines Register. Revised New 1956 edition 25.00

GEOCHEMISTRY, CHEMICAL GEOLOGY

Geochemistry. By V. M. GOLDSCHMIDT edited by Alex Muir. 1954. Pp. 730, tbls. 96 ..... 11.20

Principles of Geochemistry. By BRIAN MASON. 1958. Pp. 309. Illus. 8.50

Isotope Geology. By KALERVO RANKAMA. 1955. Pp. 550 ..... 12.00

Nuclear Geology. By HENRY FAUL. 1954. Pp. 414 ..... 7.00

Geochemistry. By KALERVO RANKAMA and TH. G. SAHAMA. 1950. Pp. 900. Illus. 60 ..... 15.00

Physics and Chemistry of the Earth. Vol. 1. By L. H. AHRENS, KALERVO RANKAMA, S. K. RUNCORN Eds. 1956. Pp. 317 ..... 10.00

The Principles of Chemical Weathering. By W. D. KELLER. 1955. Pp. 88. Figs. 21 ..... 3.00

(*Continued on Page xviii*)

(*Continued from Page xvii*)

BOOKS IN GEOLOGICAL SCIENCE

GEOCHEMISTRY, CHEMICAL GEOLOGY (Continued)

General Chemistry. 2nd Ed. By LINUS PAULING. 1953. Pp. 722. Illus. 193 including 2 color plates. Tables 33 ..... 6.50

The Physical Chemistry of the Silicates. By WILHELM EITEL. 1954. Pp. 1592, figs. 952 ..... 45.00

Silicate Analysis: A Manual for Geologists and Chemists, with Chapters on Check Calculations and Geo-Chemical Data. By A. W. GROVES and Foreword by ARTHUR HOLMES. 1951. Pp. 336 ... 5.50

Differential Thermal Analysis. By W. J. SMOTHERS and YAO CHIANG. 1957. Pp. 530. Illus. 16.00

Rocks for Chemists. An Introduction to the Study of Rocks from the Viewpoint of Chemistry. By S. J. SHAND. 1952. Illus. 4.50

Radiocarbon Dating. By WILLARD F. LIBBY. 1951. Pp. 122. Illus. 4.50

Spectrochemical Analysis. By L. H. AHRENS. 1st Ed. 2nd ptg. 1954. Pp. 354. Illus. 12.00

Wavelength Tables of Sensitive Lines. By L. H. AHRENS. 1st Ed. 2nd ptg. 1954. Pp. 86 ..... 3.00

GEOPHYSICS, GEOPHYSICAL EXPLORATION

Advances in Geophysics. Volume I. By H. W. LANDSBERG. 1952. Pp. 362. XII. Illus. 8.50

Advances in Geophysics. Vol. 3. By H. E. LANDSBERG, Ed. 1956. Pp. 378 ..... 8.80

Fundamentals of Physical Science. By KONRAD B. KRAUSKOPF. 3rd Ed. Pp. 694 ..... 6.00

Lectures on Rock Magnetism. By P. M. S. BLACKETT. 1954. Pp. 131 ..... 5.00

The Atomic Nucleus. By ROBLEY D. EVANS. 1955. Pp. 972. Illus. 14.50

The Geometry of Geodesics. By HERBERT BUSEMANN. 1955. Pp. 422 ..... 9.00

An Introduction to the Theory of Seismology. By K. E. BULLEN. 2nd Ed. 1954. Pp. 296. Figs. 42 ..... 6.50

Seismology. By K. E. BULLEN. 1954. Pp. 132. Figs. 15 ..... 2.00

Seismicity of the Earth and Associated Phenomena. By B. GUTENBERG and C. F. RICHTER. Revised 1954. Pp. 277. Maps. 154 pages of tables 10.00

Elastic Waves in Layered Media. By W. M. EWING, F. PRESS, W. S. JARDETZKY. 1957. Pp. 375 .. 10.00

Internal Constitution of the Earth. Edited by B. GUTENBERG. 1951. Pp. 439. Tables 88. Illus. 43 ..... 2.45

Seismic Prospecting for Oil. By CHARLES HEWITT DIX. Pp. 414. Illus. 175 ..... 8.00
Textbook edition available for classroom use 6.00

Introduction to Geophysical Prospecting. By M. B. DOBRIN. 1952. Pp. 435. Illus. 265 ..... 8.00

Exploration Geophysics. By J. JAY JAKOSKY. 1950. Pp. 1200 ..... 12.50

Manual on Geophysical Prospecting with the Magnetometer. 2nd. Ed. By JAMES WALLACE JOYCE. 1948. Pp. 137 ..... 6.00

Applied Geophysics in the Search for Minerals. 4th Ed. By A. S. EVE and D. A. KEYS. 1954. Pp. 382 ..... 9.50

The Fundamentals of Electric Log Interpretation. By M. R. J. WYLLIE. 1957. Pp. 176. Illus. Ed. 2. 4.50

Electrical Well Logging Fundamentals. By H. GUYOD. 1952. Pp. 164. Illus. 257 ..... 3.75

Geophysical Prospecting for Oil. By LEWIS L. NETTLETON. 1940. Pp. 444 ..... 8.00

Earth Waves. By L. DON LEET. 1950. Pp. 122. Illus. 69 ..... 3.90

Sonics. By THEODOR F. HUETER and RICHARD H. BOLT. 1955. Pp. 456. Illus. 231 ..... 10.00

The New Physics. By SIR C. V. RAMAN. 1951. Pp. 144 ..... 3.75

GEOMORPHOLOGY, PHYSICAL GEOLOGY, PHYSIOGRAPHY

Geographical Essays. By W. M. DAVIS. 1909. Republished unabridged, 1954. Pp. 777. Figs. 130 ..... 2.95

Physical Geology. By L. DON LEET and SHELDON JUDSON. 1954. Pp. 466 ..... 9.00

Physical Geology. 3rd Ed. By CHESTER R. LONGWELL, ADOLPH KNOPF, and RICHARD F. FLINT. 1948. Pp. 602. Illus. 365 ..... 6.50
Visual Aids Kit 85.00

Introduction to Physical Geology. By C. R. LONGWELL and R. F. FLINT. Pp. 432. Figs. 308, Tbl. 12, Pls. 2 ..... 4.95

A Textbook of Geology. By R. M. GARRELS. 1951. Pp. 511 ..... 6.00

Principles of Geomorphology. By WILLIAM D. THORNBURY. 1954. Pp. 618. Figs. 275 ..... 8.00

Principles of Geology. By JAMES GILLULY, AARON C. WATERS, and A. O. WOODFORD. 1951. Pp. 640. Illus. 306 ..... 6.00

Geology. By VON ENGELN, O. E., and CASTER, K. E. 1952 ..... 7.50

General Principles of Geology. By J. F. KIRKLADY. 1955. Pp. 327. Pls. 6, Figs. 84 ..... 10.00

The Principles of Physical Geology. By V. E. MONNETT and H. E. BROWN. 1950. Pp. 450. Illus. 265 plus 16 topographic maps 4.75

Physical Geography. By A. H. STRAHLER. 1951. Pp. 442 ..... 6.75

Introduction to Geology. 3rd Ed. By E. B. BRANSON, W. D. KELLER, and W. A. TARR. 1952. Pp. 482. Illus. 6.00

Climatic Accidents in Landscape-Making. By CHARLES A. COTTON. 1948. Pp. 354. Illus. 267 ... 7.00

Geology: Principles and Processes. By WM. H. EMMONS, GEO. A. THIEL, CLINTON STAUFFER, IRA S. ALLISON. 4th Ed. 642 Pp. 6.50

Principles of Physical Geology. By ARTHUR HOLMES. 1945. Pp. 532. Pls. 95. Figs. 262 ..... 5.00

Physical Geology and Man. By KENNETH K. LANDES. 1948. Pp. 414. Figs. 164 ..... 6.65

Down to Earth. 2nd Rev. Ed. By C. CRONEIS and W. C. KRUMBEIN. 1947. Pp. 538. Pl. 64. Figs. 344 ..... 6.50

(*Continued on Page xix*)

(*Continued from Page xviii*)

BOOKS IN GEOLOGICAL SCIENCE

GEOMORPHOLOGY, PHYSICAL GEOLOGY, PHYSIOGRAPHY (Continued)

Textbook of Geomorphology. 2nd Ed. By PHILLIP G. WORCESTER. 1948. Pp. 584. Illus. Maps. 6.25

Outlines of Physical Geology. 2nd Ed. By CHESTER R. LONGWELL, ADOLPH KNOPF, and R. F. FLINT. 1941. Pp. 387. Illus. 281. 5.00

Morphological Analysis of Land Forms. By WALTHER PENCK. (Translated by HELLA CZECH and KATHERIN C. BOSWELL). 1953. Pp. 429. Figs. 21. Pls. 12. 8.50

Geology. 5th Ed. By P. LAKE and R. H. RASTALL. 1941. Pp. 491. Figs. 129. 5.25

Geomorphology. By A. K. LOBECK. 1939. Pp. 731. Fully Illus. 9.50

Introduction to Physical Geology with Special Reference to North America. 5th Ed. Revised by W. J. MILLER. 1949. Pp. 482. Illus. Maps. 5.00

Outlines of Geology. 2nd Ed. Contains Outlines of Physical Geology. By CHESTER R. LONGWELL, ADOLPH KNOPF, and RICHARD FLINT; and Outlines of Historical Geology by CHARLES SCHUCHERT and CARL O. DUNBAR. 1941. Pp. 672. Illus. 431. 7.25

Laboratory Manual for Geology. By K. F. MATHER, C. J. ROY and L. R. THIESMEYER

Part I. Physical Geology (Revised). 1950. Pp. 165. Illus. 25 Line, 4 HT. 2.75

Part II. Historical Geology. 1952. Pp. 252. Illus. 80 Line, 1 HT. 2.75

Earth Science: The World We Live In. By SAMUEL N. NAMOWITZ and DONALD B. STONE. 1953. Pp. 438. 3.96

Waves and Tides. By R. C. H. RUSSEL and D. H. MACMILLAN. 1953. Pp. 348. Pls. 17. Figs. 100 6.00

The Sea Coast. By J. A. STEERS. "New Naturalist Series". 1951. Pp. 276. Figs. 52. 3.75

Dynamical Oceanography. By J. PROUDMAN. 1953. Pp. 409. 8.50

The Galathea Deep Sea Expedition 1950–52. By ANTON F. BRUUN, SV. GREVE, HAKON MIELCHE, RAGNAR SPARCK. Translated from Danish by R. SPINK. 1956. Pp. 296, Illus. 8.00

The Tetons (Interpretations of a Mountain Landscape). By FRITIOF FRYXELL. 3rd printing, 1953. 92 Pp., 24 Illus. 2.00

The Incomparable Valley—A Geologic Interpretation of the Yosemite. By FRANCOIS E. MATTHES; edited by FRITIOF FRYXELL. 1950. Pp. 176. Frontis. 50 Illus. 11 Figs. 2 maps. 3.75

Crater Lake (The Story of Its Origin). By HOWELL WILLIAMS, 3rd printing. 1954. 114 Pp., 25 Illus. 2.00

South African Scenery, A Textbook of Geomorphology. 2nd Rev. and Enlarged Edition. By L. C. KING. 1951. Pp. 412. Illus. 267, 79 text figures, 1 folding map, 1 colored erosion map. 6.37

Manual for Physical Geology. By PERCIVAL ROBERTSON. 1953. Pp. 101. 2.75

Physiography of Eastern United States. By NEVIN M. FENNEMAN. 1938. Pp. 714. Illus. Cloth. 10.00

Physiography of Western United States. By NEVIN M. FENNEMAN. 1931. Pp. 534. 9.00

The Physiographic Provinces of North America. By W. W. ATWOOD. 1940. Pp. 536. Illus. 281. 6.00

The Oceans: Their Physics, Chemistry, and General Biology. By H. U. SVERDRUP, M. W. JOHNSON, and R. H. FLEMING. 1942. Pp. 1087. 13.50

The Ocean. By F. D. OMMANNEY. 1949. Pp. 247. Pl. 4. Figs. 12. Bibliography Maps. 1.00

Submarine Geology. By FRANCIS PARKER SHEPARD. 1948. Pp. 348. Illus. 6.00

Marine Geology. By PH. H. KUENEN. 1950. Pp. 568. Illus. 250. 8.00

The Ocean Floor. By HANS PETTERSSON. 1954. Pp. 181. Figs. 48. 3.00

Handbuch der Gletscherkunde und Glazialgeologie. By KLEBELSBERG. PROF. DR. R. 1948–49. 2 Bde. 40.00

Steam Blast Volcanic Eruptions. A Study of Mount Pelee in Martinique as Type Volcano. By THOMAS A. JAGGAR. 1949. Figs. 41. 2.00

Volcanological Observations. By FRANK ALVORD PERRET. 1950. Quarto, Pp. 162. Figs. 117 paper, 5.00

Catalogue of the Active Volcanoes of the World Including Solfatara Fields. Part I. Indonesia. By M. NEUMANN VAN PADANG. Ed. by the International Volcanological Assoc. 1951. Pp. 271. Figs. 117. 5.00

Our Amazing Earth. By C. L. FENTON. Reissue 1945. Pp. 368. 39 pages halftones. 95 line drawings. 4.75

Earth Sciences. By J. HARLEN BRETZ. 1940. Pp. 260. Illus. 122. 3.00

METAMORPHIC, STRUCTURAL AND FIELD GEOLOGY

Metamorphism. A Study of the Transformation of Rock-Masses. 3rd Ed. By ALFRED HARKER. 1950. Pp. 362. Figs. 185. Cloth, 6 x 9. 5.50

The Origin of Metamorphic and Metasomatic Rocks. By HANS RAMBERG. 1953. Pp. 352. Illus. 10.00

Deformation of the Earth's Crust. By WALTER H. BUCHER. 1957. Pp. 578. 10.00

Structural Geology. By L. U. DE SITTER. 1956. Pp. 552. Figs. 309. Tables 15. 11.00

Graphic Methods in Structural Geology. By WM. L. DONN and J. A. SHIMER. 1958. Pp. 180. Figs. 104. 4.00

Structural Geology Manual. By JOHN C. LUDLUM and JOHN M. DENNISON. 1957. Pp. 115. Figs. 47 2.50

Principles of Structural Geology. 4th Ed. By C. M. NEVIN. 1949. Pp. 410. Illus. 250. 6.00

Structural Geology. By MARLAND P. BILLINGS. 2nd Ed. 1954. Pp. 473. Figs. 336. Pls. 19. 10.00

Mountain Building. By REIN W. VAN BEMMELEN. 1954. Pp. 189, figs. 51. 4.00

Structural Geology of North America. By A. J. EARDLEY. 1951. Pp. 624. 13.50

The Tectonics of Middle North America. By PHILIP B. KING. 1951. Pp. 224. 52 Maps. 3.75

(*Continued on Page xx*)

(*Continued from Page xix*)

BOOKS IN GEOLOGICAL SCIENCE

METAMORPHIC, STRUCTURAL AND FIELD GEOLOGY (Continued)

Outline of Structural Geology. 3rd Ed. By E. S. HILLS. 1953. Pp. 170 ..... 3.50

The Dynamics of Faulting and Dyke Formation with Applications. 2nd Ed. By ERNEST M. ANDERSON. 1951. Pp. 216. Figs. 39 ..... 4.00

Field Geology. 5th Ed. By F. H. LAHEE. 1952. Pp. 853. Illus. 5 x 7½ 9.50

Geologic Field Methods. By JULIAN W. LOW. 1957. Pp. 489. Line Drawings 214 ..... 6.00

Structural Geology for Petroleum Geologists. By WILLAIM L. RUSSELL. 1955. Pp. 427. Figs. 159. Tables 5 ..... 7.50

Principles of Field and Mining Geology. By JAMES D. FORRESTER. 1946. Pp. 647. Illus. 316 ..... 8.75

The Use of Stereographic Projection in Structural Geology. By F. C. PHILLIPS. 1954. Pp. 86. Figs. 86 ..... 3.75

METEOROLOGY AND CLIMATE

Climatic Atlas of the United States. By STEPHEN SARGENT VISHER. 1954. Pp. 403. Illus. 9.00

Climatic Change: Evidence, Causes, and Effects. Ed. by HARLOW SHAPLEY. 1953. P. 318. Figs. 58 ..... 6.00

The Climate Near the Ground. By R. GEIGER. 1950. Pp. 482. Figs. 181. Tables 63 ..... 6.00

The Atmospheres of the Earth and Planets. Rev. Ed. By GERARD P. KUIPER. 1952. Pp. 416 ..... Paper $5.50; Cloth 8.50

Cloud Physics. By D. W. PERRIE. 1951. Pp. 119. Pls. 4.50

Weather Elements. 3rd Ed. By T. A. BLAIR. 1948. Pp. 373 ..... 6.35

Descriptive Meteorology. By HURD C. WILLETT. 1952. Pp. 310. VIII 6.00

Dynamic Meteorology. By HOLMBOE, FORSYTHE and GUSTIN. 1945. Pp. 378. Illus. 222 ..... 6.00

General Meteorology. By HORACE R. BYERS. 1944. Pp. 645. Illus. 284. Tables 27 ..... 7.50

Meteorology, Theoretical and Applied. By E. W. HEWSON and R. W. LONGLEY. 1944. Pp. 468. Illus. 193 ..... 7.00

Handbook of Meteorology. By FREDERIC A. BERRY, E. BALLAY and N. R. BEERS. 1945. Pp. 1116 ..... 13.50

Climatology. By BERNARD HAURWITZ and JAMES M. AUSTIN. 1944. Pp. 410 ..... 8.00

Climatology. By T. A. BLAIR. 1942. Pp. 484 ..... 7.65

Techniques of Observing the Weather. By BENARTHUR C. HAYNES. 1947. Pp. 272. Illus. 98 ..... 4.90

Air Pollution: Proceedings of the U. S. Technical Conference on Air Pollution. By L. C. MCCABE. 1952. Pp. 847 ..... 12.50

MINERAL ECONOMICS, GEOPOLITICS

Economics of Atomic Energy. By MARY S. GOLDRING. 1957. Pp. 179 ..... 6.00

Facing the Atomic Future. By E. W. TITTERTON. 1956. Pp. 379 ..... 5.00

Minerals in World Industry. By WALTER H. VOSKUIL. 1955. Pp. 316. Tables 38. Figs. 26 ..... 5.75

The Mineral Resources of the World. By VAN ROYEN and BOWLES. 1952. Volume II. Pp. 180. Figs. 186 ..... 12.00

An Encyclopedia of the Iron and Steel Industry. By A. K. OSBORNE. Pp. 558. Pls. 16. Figs. 9. 1956 ..... 25.00

Conservation of Natural Resources. Ed. by GUY-HAROLD SMITH. 1950. Pp. 552. Illus. 6.75

The Future of Our Natural Resources. Volume 281 of The Annals of the American Academy of Political and Social Science. By STEPHEN RAUSHENBUSH. May, 1952. Pp. 275 ..... 2.00

The Earth and Its Resources. 2nd Ed. By V. C. FINCH, M. T. TREWARTHA, and M. H. SHEARER. 1948. Pp. 584. Illus. 463 ..... 4.80

Out of the Earth. By G. B. LANGFORD. 1954. Pp. 140, pls. 14, figs. 28, tbls. 3 ..... 3.50

Science and Economic Development: New Patterns of Living. By RICHARD L. MEIER. 1956. Pp. 247. Tbls. 22. Figs. 28 ..... 6.00

Natural Resources Utilization in a Background of Science and Technology. Vol. 1: Geology and Geography. By JAMES C. MALIN. 1950. Pp. 377. Illus. 5. Lithoprint from typescript, paper cover 2.50

The Agricultural Resources of the World. By WM. VAN ROYEN. 1954. Pp. 258. Figs. 338 (Vol. I of Atlas of World Mineral Resources) 13.35

Resource Conservation: Economics and Policies. By CIRIACY-WANTRUP. 1952. Pp. 396 ..... 6.50

World Population and Future Resources. The Proceedings of the Second Centennial Academy Conference of Northwestern University, Evanston, Ill. By P. K. HATT. 1952. Pp. 280 ..... 3.50

Conservation in the United States. 3rd Ed. By GUSTAFSON, GUISE, HAMILTON, JR., and RIES (Members of the faculty of Cornell University). 1949. Pp. 543. Tables 21 ..... 5.00

A Conservation Handbook. By SAMUEL H. ORDWAY, JR. 1949. Pp. 76 ..... 1.00

Economics of Natural Gas in Texas. By J. R. STOCKTON, R. C. HENSHAW, JR. and R. W. GRAVES. 1952. Pp. 316. Pls. 38. Figs. 19. Tables 87 ..... 5.00

Arabian Oil—America's Stake in the Middle East. By RAYMOND F. MIKESELL and HOLLIS B. CHENERY. 1949. Pp. 216. 19 tables 3.50

Minerals in World Affairs. By THOMAS S. LOVERING. 1943. Pp. 394. Tables 50 ..... $4.75 to schools 6.35

Energy Sources—The Wealth of the World. By EUGENE AYRES and CHARLES A. SCARLOTT. 1952. Pp. 344 ..... 5.00

World Minerals and World Peace. By CHARLES K. LEITH, J. W. FURNESS and CLEONA LEWIS. 1943. Pp. 253. Pls. 15. Tables 41 ..... 2.50

(*Continued on Page xxi*)

(*Continued from Page xx*)

BOOKS IN GEOLOGICAL SCIENCE

MINERAL ECONOMICS, GEOPOLITICS (Continued)

The Porphyry Coppers in 1956. By A. B. PARSONS. 1957. Pp. 270 ..... 5.00

Minerals—A Key to Soviet Power. By DEMITRI B. SHIMKIN. 1953. Pp. 452. Figs. 8. Tables 101 8.00

Seventy-five Years of Progress in the Mineral Industry (1871–1946) American Institute of Mining and Metallurgical Engineers. By A. B. PARSONS, *Editor*. 1947. Pp. 817 ..... 5.00

MINING

Elements of Mining. 4th Ed. By G. J. YOUNG. 1946. Pp. 755. Illus. 382 ..... 9.00

The Basis of Mine Surveying. By M. H. HADDOCK. 1952. Pp. 301. Fig. 246 ..... 5.50

Mining Year Book. By WALTER E. SKINNER. 1953. Pp. 856 ..... 7.00

Mines Register, 1952 Rev. Ed. Successor to **The Mines Handbook (Descriptions of mines and mining companies).** Pp. 730 ..... 25.00

Handbook for Prospectors and Operators of Small Mines. 4th Ed. By MAX W. VON BERNEWITZ—Revised by HARRY C. CHELLSON. 1943. Pp. 547. Illus. 161. 5 x 7½ 7.50

Mining Engineer's Handbook. By ROBERT PEELE, *Editor*. 3rd Ed. 1941. 2 Vols. 18.50

Examination and Valuation of Mineral Property. By ROLAND D. PARKS. 3rd Ed. 2nd ptg., 1952. Pp. 504. Illus. 8.50

PALEONTOLOGY, STRATIGRAPHY, HISTORICAL GEOLOGY

Historical Geology. By CARL O. DUNBAR. 1949. Pp. 567. Illus. 380 ..... 7.25

Introduction to Historical Geology. By RAYMOND C. MOORE. 1949. Pp. 582. Illus. Maps 6.75

Historical Geology. By RAYMOND C. MOORE. 1933. Pp. 673. Figs. 413 ..... 8.50

Historical Geology—The Geologic History of North America. 2nd Ed. By RUSSELL C. HUSSEY. 1947. Pp. 465. Illus. 344 ..... 5.75

Geology: An Introduction to Earth History. By H. H. READ. 1949. Pp. 256. Illus. 30. Maps ... 1.20

The Principles of Historical Geology. By J. WILLIS STOVALL and H. E. BROWN. 1954. Pp. 472. Illus. 200 ..... 6.00

An Introduction to Historical Geology. 6th Ed. By W. J. MILLER. 1952. Pp. 555. Illus. 5.50

The Origin and History of the Earth. By ROBERT TUNSTALL WALKER and WOODVILLE JOSEPH WALKER. 1954. Pp. 244. Illus., Figs. ... U.S., 5.00; Canada & Mexico, 5.25; Other Countries 5.50

The Planets: Their Origin and Development. By HAROLD C. UREY. 1952 ..... 5.00

The Origin of the Earth. By W. M. SMART. 1951. Pp. 239 ..... 3.50

Geology and Man. By KENNETH K. LANDES and RUSSELL C. HUSSEY. 1948. Pp. 518. Figs. 188. 7.65

Introduction to College Geology. By CHAUNCEY D. HOLMES. 1949. Pp. 429; figs. 312; tables 4.50

Glacial and Pleistocene Geology. By R. F. FLINT. 1957. Pp. 553 ..... 12.50

Glacial Geology and the Pleistocene Epoch. By RICHARD F. FLINT. 1947. Pp. 589. Illus. 94 .... 12.50

Prehistory and Pleistocene Geology in Cyrenaican Libya. By C. B. M. MCBURNEY and R. W. HEY. 1955. Pp. 315. Figs. 40. Pls. 16 ..... 10.00

Outlines of Historical Geology. 4th Ed. By CARL O. DUNBAR and CHARLES SCHUCHERT. 1941. Pp. 291. Illus. 176 ..... 4.50

Atlas of Paleographic Maps of North America. By CHARLES SCHUCHERT. 1955. Pp. 177 ..... 4.75

Jurassic Geology of the World. By W. J. ARKELL. 1956. Pp. 806. Figs. 102. Pls. 16. Correlation Tables 28 ..... 16.50

Record of the Rocks. By HORACE G. RICHARDS. 1953. Pp. 413. Figs. 294 ..... 6.00

An Introduction to Stratigraphy. 2nd Edition, revised. By L. D. STAMP. 1950. Pp. 381 ..... 3.25

Principles of Stratigraphy. By C. O. DUNBAR and J. RODGERS. 1957. Pp. 356 ..... 10.00

Stratigraphic Geology. By MAURICE GIGNOUX. 1955. Pp. 830. Fig. 155 ..... 9.50

Stratigraphical Paleontology—a Study of Ancient Life-Provinces. By E. NEAVERSON. 2nd Ed. 1955. Pp. 806. Figs. 90 ..... 16.80

Principles of Invertebrate Paleontology. By R. P. SHROCK and W. H. TWENHOFEL. 2nd Ed. 1953. Illus. 488. Pp. 816 ..... 12.50

Outlines of Paleontology. 3rd Ed. By H. H. SWINNERTON. 1947. Pp. 385. Figs. 368 ..... 6.50

Index Fossils of North America. By HERVEY W. SHIMER and ROBERT P. SHROCK. 1944. Pp. 837. Illus. 8,000. Pls. 303 ..... 22.00

Invertebrate Fossils. By R. MOORE, C. LALICKER and A. FISCHER. 1952. Illus. 454. Pp. 738 .... 12.50

Invertebrate Palaeontology. 8th Ed. Rev. and Enl. By HENRY WOODS. 1946. Pp. 477. Figs. 221 3.50

Echinodermata. Vol. IV of The Invertebrates. The coelomate bilateria. By LIBBIE HENRIETTA HYMAN. 1955. Pp. 763. Illus. 10.00

Evolution of the Vertebrates. By EDWIN H. COLBERT. 1955. Pp. 479. 125 Illus. 8.95

Paleontology and Modern Biology. By D. M. S. WATSON. 1951. Pp. 216. Figs. 77 ..... 4.00

Natural History of Marine Animals. By MACGINITIE and MACGINITIE. 1949. 473 Pp., 282 Illus. 7.50

Introduction to Microfossils. By DANIEL J. JONES. 1956. Pp. 406 ..... 6.50

Foraminifera: Their Classification and Economic Use. 4th Ed., Revised and Enlarged. By JOSEPH A. CUSHMAN. 1948. Pp. 605. Figs. 9. 31 Text Pls. 55 Key Pls. 12.50

The Invertebrates: Platyhelminthes and Rhynchocoela. The Acoelomate Bilateria, Vol. II. By LIBBIE HENRIETTA HYMAN. 1951. Pp. 550. 208 figs. 9.00

(*Continued on Page xxii*)

(*Continued from Page xxi*)

BOOKS IN GEOLOGICAL SCIENCE

PALEONTOLOGY, STRATIGRAPHY, HISTORICAL GEOLOGY (Continued)

A Textbook of Evolution. By EDWARD O. DODSON. 1952. Pp. 419. Illus. 101 ..... 5.00

Evolution Emerging. By W. K. GREGORY. 1951.
Vol. I. Pp. 736. Vol. II. Pp. 1013 ..... Boxed set of two volumes 20.00

The Meaning of Evolution, A Study of the History of Life and its Significance for Man. By G. G. SIMPSON. 1950. Pp. 364. Illus. 4.00

The Origin of Vertebrates. By N. J. BERRILL. 1955. Pp. 257. Illus. 4.00

The Principles of Classification and a Classification of Mammals. By G. G. SIMPSON. 1945. Vol. 85. Pp. 350 ..... 3.50

Horses: the Story of the Horse Family in the Modern World Through Sixty Million Years of History. By G. G. SIMPSON. 1951. Pp. 247. Illus. 32 ..... 6.50

Time's Arrow and Evolution. By HAROLD F. BLUM. 1951. Pp. 222 ..... 4.00

Genetics Paleontology and Evolution. By G. L. JEPSEN, ERNST MAYR, and GEORGE G. SIMPSON (ed.). 1949. Pp. 448. Illus. 7.50

History of the Primates. 2nd Ed. By W. E. LE GROS CLARK, F.R.S. 1950. Pp. 118. 40 text-figures ..... .85

The Dinosaur Book: The Ruling Reptiles and Their Relatives. By E. H. COLBERT. 1951. Pp. 156. Illus. 6.50

On the Origin of Species. By CHARLES DARWIN. Reprinted 1951 of 1859 Edition. Pp. 426 ..... 3.75

The Fossil Evidence for Human Evolution. By W. E. LE GROS CLARK. 1955. Pp. 181 ..... 6.00

Finding Fossil Man. By ROBIN PLACE. 1957. Pp. 126. Figs. 46. Pl. 63 ..... 7.50

Man, the Tool-Maker. 2nd Ed. By K. P. OAKLEY. 1950. Pp. 98. 41 text-figures 1.00

Strange Story of our Earth. By A. H. VERRILL. 1952. Pp. 255. Illus. 72 ..... 3.75

The Story of Life. By H. E. L. MELLERSH. 1958. American Edition 1. Pp. 263. Illus. 3.95

The Succession of Life through Geological Time. By K. P. OAKLEY and H. M. MUIR-WOOD. 2nd Ed. 1949. Pp. 92. Pls. 12 and 4 maps 2s 6d

Life Through the Ages. By CHARLES R. KNIGHT. 1946. Pp. 66 ..... 2.50

Life Through the Ages. By R. W. BURNETT. 1947. Pp. 48. Illus. 1.00

The Living Rocks. Translated by JOYCE EMERSON and STANLEY A. PACOCK. Photographs by S. CELEBONOVIC with a commentary by GEOFFREY GRIGSON and a preface by ANDRE MAUROIS. 1957. Pp. 94 ..... 6.00

The Search Beneath the Sea. By J. L. B. SMITH. 1956. Pp. 260. Illus. 3.95

American Seashells. By R. RUCKER ABBOTT. 1954. Pp. 541. Figs. 100. Pls. 40 ..... 12.50

Creatures of the Deep Sea. By KLAUS GUNTHER and KURT DECKERT. Translated by E. W. DICKES. 1956. Pp. 222 ..... 3.95

Introduction to Paleobotany. By CHESTER A. ARNOLD. 1947. Pp. 433 ..... 8.00

An Introduction to the Study of Fossil Plants. By JOHN WALTON. 1940. Pp. 188. Illus. 4.75

Procedure in Taxonomy. By E. T. SCHENK and J. H. MCMASTERS. Revised Ed. 1948. Pp. 93 ..... 3.50

Examination of Well Cuttings. By JULIAN W. LOW. 48 Pp. 13 schematic illustrations. 1952 ..... 1.50

PETROLOGY, SEDIMENTATION

The Evolution of the Igneous Rocks. By N. L. BOWEN. With a new introduction by J. F. SCHAIRER. 1956. Pp. 332 ..... 1.85

Petrology for Students. 8th Ed. By ALFRED HARKER; revised by C. E. TILLEY, S. R. NOCKOLDS, and M. BLACK. 1954. Pp. 283 ..... 3.50

Guide to the Study of Rocks. A part of the Harpers Geoscience Series. By L. E. SPOCK. 1953. Pp. 256. Line cuts 34 ..... 4.50

A Descriptive Petrography of the Igneous Rocks. 1931–38. By A. JOHANNSEN.
Vol. I—Introduction, Textures, Classifications, and Glossary. Rev. Ed. 1939. Pp. 318 ..... 6.00
Vol. II—The Quartz-Bearing Rocks. 1932. Pp. 438. Diagrams 9. Photographs 16. Photomicrographs 66. Portraits 32. Tables 209 ..... 8.00
Vol. III—The Intermediate Rocks. 1937. Pp. 360. Diagrams 4. Photographs 18. Photomicrographs 114. Portraits 47. Tables 108 ..... 7.00
Vol. IV—Part I. The Feldspathoid Rocks; and Part II. The Peridotites and Perknites. 1938. Pp. 551. Diagram 8. Photographs 9. Photomicrographs 95. Portraits 77. Tables 159 ..... 10.00

Textbook of Petrology.
Vol. 1: The Petrology of the Igneous Rocks. 10th Ed. By F. H. HATCH, A. K. WELLS, and M. K. WELLS. 1950. Pp. 469 ..... 4.50
Vol. 2: The Petrology of the Sedimentary Rocks. 3rd Ed. revised by MAURICE BLACK. 1938. By F. H. HATCH and R. H. RASTALL. 1913. Reprinted 1950. Pp. 383. Illus. 75. Tables 15 ..... 6.75

Petrography. Part I—Igneous Rocks; Part II—Metamorphic Rocks; Part III—Sedimentary Rocks. By HOWEL WILLIAMS, FRANCIS J. TURNER and CHARLES M. GILBERT. 1954. Pp. 416. 133 Illus. 8.00

Microscopic Petrography. By E. WILLIAM HEINRICH. 1956. Pp. 296. Illus. 70 ..... 6.50

Gesteine und Minerallagerstatten, Allgemeine Lehre von den Gesteinen und Minerallagerstaatten. By PAUL NIGGLI. 1952. Pp. 554. Figs. 181
Vol. I 12.00
Vol. II 12.00

(*Continued on Page xxiii*)

(*Continued from Page xxii*)

BOOKS IN GEOLOGICAL SCIENCE

PETROLOGY, SEDIMENTATION (Continued)

Einfuhrung in die gesteinkunde. By H. LEITMEIER. 1950. Pp. 275 ..... 5.00

Igneous and Metamorphic Petrology. By F. J. TURNER and J. VERHOOGEN. 1951. Pp. 490 ..... 9.50

The Origin of Metamorphic and Metasomatic Rocks. By HANS RAMBERG. 1953. Pp. 352. Illus. 130 charts, graphs, photographs and line drawings 10.00

Theoretical Petrology. By T. F. W. BARTH. 1952. Pp. 387. Illus. 6 x 9¼ 7.75

Introduction to Theoretical Igneous Petrology. By ERNEST E. WAHLSTROM. 1950. Pp. 365; numerous figs. and tables 6.50

Petrographic Modal Analysis. By FELIX CHAYES. 1956. Pp. 113. Figs. 14 ..... 5.50

A Historical Survey of Petrology. By F. J. LOEWINSON-LESSING translated by S. I. TOMKEIEFF. 1954. Pp. 112 ..... 2.25

Petrographic Mineralogy. By ERNEST E. WAHLSTROM. 1955. Pp. 408 ..... 7.75

Rocks and Rock Minerals. By LOUIS V. PIRSSON and ADOLPH KNOPF. 1947. Pp. 349. Pls. 36. Figs. 72 ..... 6.00

Rocks and Minerals. By RICHARD M. PEARL. 1956. Pp. 275. Pls. 12. Figs. 35 ..... 1.95

Rocks and Mineral Deposits. By PAUL NIGGLI (English Translation by ROBERT L. PARKER). 1954. Pp. 572. Figs. 331, tbls. 73 ..... 12.00

Les Pegmatites—Les Pegmatites Granitiques. By A. E. FERSMAN. 1951. Pp. 675.
Vol. I—Partie Preliminaire. Chaps. 1-10
Vol. II—Partie Descriptive. Chaps. 11-18
Vol. III—Partie Generale. Chaps. 19-25 ..... 18.00

The Study of Rocks. 4th Ed. By S. J. SHAND. 1951. Pp. 236 ..... 2.25

Igneous Minerals and Rocks. By ERNEST E. WAHLSTROM. 1947. Pp. 367. Illus. 6.50

Structural Petrology of Deformed Rocks. 2nd Ed. 2nd Ptg. By HAROLD W. FAIRBAIRN and FELIX CHAYS. 1954. Pp. 344; numerous figs. and tables 12.50

Petrography and Petrology. By FRANK F. GROUT. 1932. Pp. 522 ..... 8.00

Igneous Rocks and the Depths of the Earth. 2nd Ed. By REGINALD A. DALY. 1933. Pp. 598 ..... 11.00

Minerals and Rocks. By RUSSELL D. GEORGE. 1943. Pp. 595. Figs. 150. Pls. 48 ..... 6.00

Photomicrography. By CHARLES P. SHILLABER. 1944. Pp. 773. Illus. 291 ..... 15.00

Applied Sedimentation. A Symposium edited by PARKER D. TRASK. 1950. Pp. 707. Illus. 134 ..... 7.50

Principles of Sedimentation. 2nd Ed. By W. H. TWENHOFEL. 1950. Pp. 673. Figs. 81 ..... 9.00

Methods of Study of Sediments. By W. H. TWENHOFEL and S. A. TYLER. 1941. Pp. 183. Illus. 4.50

Sedimentary Rocks. 2nd Ed. By F. J. PETTIJOHN. Pp. 720. Line drawings 173. Pls. 40. Photomicrographs 100 ..... 12.00
Textbook edition available for classroom use 9.00

Stratigraphy and Sedimentation. By W. C. KRUMBEIN and L. O. SLOSS. 1951. Pp. 507. Illus. 123. Line Drawing 6.50

The Composition and Origin of the Antrim Laterites and Bauxites. By V. A. EYLES. 1952. Pp. 90, pls. 2, tbls. 10 ..... 12s6d

Problems of Clay and Laterite Genesis. By AIME. 1952. Pp. 252. AIME Members 4.20
Nonmembers 6.00

Abrasion Hardness. By THOMAS A. JAGGAR. 1950. Pp. 43. Pl. 6. Figs. 5. Tables 7 ..... 2.00

An Introduction to the Study of Organic Limestones. By J. HARLAN JOHNSON. Rev. Ed. 1951. Pp. 185. Illus. 104 ..... 2.00

An Introduction to the Study of Rock Building Algal Limestones. By J. HARLAN JOHNSON. Pp. 117. Illus. 63 ..... 2.50

Recent Sediments of the Gulf of Paria, Reports of the Orinoco Shelf Expedition. Vol. I. By TJ. VAN ANDEL and H. POSTMA. 1954. Pp. 245. Figs. 78. Append. 11. Pls. 7. Maps 4 ..... 6.50

Sequence in Layered Rocks. By ROBERT R. SHROCK. 1948. Pp. 507 ..... 9.00

Manual of Sedimentary Petrography. By KRUMBEIN and PETTIJOHN. 1938. Pp. 549. Figs. 262 .. 6.50

The Examination of Fragmental Rocks. By F. G. TICKELL. New Ed. 1947. Pp. 154. Line Drawings 5.00

Micromeritics, The Technology of Fine Particles. 2nd Ed. By JOSEPH M. DALLA VALLE. 1948. Pp. 555. Figs. 131 ..... 10.00

The Rock Book. By C. L. FENTON and M. A. FENTON. 1940. Pp. 376. 48 pp. Photo. 40 figs. ... 7.50

Soil. By G. V. JACKS. 1955. Pp. 221. Pls. 10. Figs. 5 ..... 5.00

Factors of Soil Formation. By HANS JENNY. 1941. Pp. 281. 6 x 9 Illus. 5.50

A Bibliography on Meteorites. By HARRISON BROWN, Editor. 1953. Pp. 686 ..... 10.00

(*Continued on Page xxiv*)

(*Continued from Page xxiii*)

BOOKS IN GEOLOGICAL SCIENCE

HISTORICAL AND BIOGRAPHICAL

Sir James Jeans. A Biography. By E. A. MILNE. 1953. Pp. 176 ..... 4.00

The Life and Times of Alexander von Humboldt, 1769–1859. By HELMUT DE TERRA. 1955 ..... 5.75

The Birth and Development of the Geological Sciences. By F. D. ADAMS. 1955. Pp. 511. Illus. 91 ..... 2.00

Blazing Alaska's Trails. By ALFRED H. BROOKS. 1953 ..... 4.50

Life and Letters of R. A. F. Penrose, Jr. By HELEN R. FAIRBANKS and CHARLES P. BERKEY. 1952. Pp. 765 ..... 4.00

Giants of Geology. By CARROLL and MILDRED FENTON. 1952. Pp. 333. Illus. 4.00

The Growth of Physical Science. 2nd Ed. By SIR JAMES JEANS. 1951. Pp. 364. Pls. 14 ..... 3.75

Evolutionary Thought in America. Edited by STOW PERSONS. 1950. Pp. 462 ..... 5.00

Giordano Bruno—His Life and Thought. With Annotated Translation of his Work on the Infinite Universe and Worlds. By DOROTHEA WALEY SINGER. 1950. Pp. 404. Illus. 6.00

Benjamin Silliman, Pathfinder in American Science. By JOHN F. FULTON and ELIZABETH H. THOMSON. 1947. Pp. 312 ..... 4.00

Journal of Research into the Geology and Natural History of the Various Countries Visited by H.M.S. Beagle. 1952. Pp. 615; pls. 16 (reprint of first edition, 1839) 7.50

Powell of the Colorado. By W. C. DARRAH. 1951. Pp. 426 ..... 6.00

The Lost Villages of England. By MAURICE BERESFORD. 1954. Pp. 445. Figs. 15. Pls. 16. Tables 18 ..... 12.00

The Bonanza Trail, Ghost Towns and Mining Camps of the West. By MURIEL SIBELL WOLLE. 1953. Pp. 476, figs. 108, maps 14 ..... 8.50

PHOTOGRAMMETRY, TOPOGRAPHY

Elements of Cartography. By ARTHUR H. ROBINSON. 1953. Pp. 254. Figs. 186. Tables 38 ..... 7.00

Plane Table Mapping. By J. W. LOW. 1951. Pp. 365 ..... 6.00

Handbook of Aerial Mapping and Photogrammetry. By L. G. TROREY. 1952. 2nd ed. rev. Pp. 80 ..... 6.00

Manual of Photogrammetry. 2nd Ed. 1952. Pp. 876 ..... 12.50

Aerial Photographs and Their Application. By HAROLD T. U. SMITH. 1943. Pp. 372. Figs. 61 ..... 5.00

Military Maps and Air Photographs. By ARMIN K. LOBECK and W. J. TELLINGTON. 1944. Pp. 256. Illus. 8½ x 11 ..... 8.00

TECHNICAL DICTIONARY, TERMINOLOGY, THESAURUS

Composition of Scientific Words. By WILBUR BROWN. 1954. Pp. 882 ..... 8.00

Multilingual Mining—Metallurgical—Geological—Mineralogical—Petrographical and Petroleum Dictionary. English-Spanish, French, German, and Russian. By ALEJANDRO NOVITZKY. 1951. Pp. 369. Sold with Alphabetical Index only 12.00

Alphabetical Index for Mining Dictionary. Spanish, French, German, and Russian. 1958 ..... 12.00

German-English and English-German Dictionary for Scientists. By O. W. LEIBIGER and I. S. LEIBIGER. 1950. Pp. 752 ..... 8.00

German-English Technical and Engineering Dictionary. By LOUIS DEVRIES. 2nd Ed. 1950. Pp. 940 ..... 20.00

German-English Technical Dictionary. 2 Volumes. By KURT F. LEIDECKER (ed.), Compiled by U. S. Air Force. 100,000 terms 35.00

English-French and French-English Technical Dictionary. By FRANCIS CUSSET. 1946. Pp. 590 ..... 5.00

Geology and Allied Sciences. A thesaurus and coordination of English and German terms. Pt. I. German-English. WALTER HUEBNER, Ed. Pp. 424. 1939. Cloth, 5½ x 8½ 7.50

Dictionary of Scientific Terms. 5th Ed. By JOHN H. KENNETH. 1953 ..... 12.50

Chambers Mineralogical Dictionary. 1948. Pp. 87. Col. Pls. 40 ..... 4.75

The Russian-English Technical and Chemical Dictionary. By LUDMILLA I. CALLAHAM. 1947. Pp. 794 ..... 15.00

Scientific German. By G. E. CONDOYANNIS. 1957. Pp. 163 ..... 2.50

Scientific French. By WILLIAM J. LOCKE. Pp. 112. 1957 ..... 2.50

Scientific Russian. By J. W. PERRY. 1951. Pp. 845 ..... 10.00

Elementary Scientific Russian Reader. By G. A. ZNAMENSKY. 1944. Pp. 107 ..... 1.75

The International Dictionary of Physics and Electronics. By WALTER C. MICHELS. 1956. Pp. 1004 ..... 20.00

Van Nostrand's Scientific Encyclopedia. By VAN NOSTRAND. 3rd Edition. 1958. Pp. 1,839 ..... 30.00

Concise International Dictionary of Mechanics and Geology. By S. A. COOPER. English-French-German-Spanish 6.00

(*Continued on Page xxv*)

(Continued from Page xxiv)

BOOKS IN GEOLOGICAL SCIENCE

TECHNICAL DICTIONARY, TERMINOLOGY, THESAURUS (Continued)

Webster's Geographical Dictionary. 1949. Pp. 1352. 177 maps, 24 color plates..... 8.50

Pocket Dictionary of Meteorology. By DR. KARL KEIL. 1950. Pp. 604 with numerous Illus..... 7.00

MISCELLANEOUS

Beyond the Hundredth Meridian—John Wesley Powell and the Second Opening of the West. By WALLACE STEGNER. 1954. Pp. 438. Figs. 12. Maps 7..... 6.00

Man's Nature and Nature's Man. By LEE R. DICE. 1955. Pp. 329..... 5.00

Men to Match My Mountains: The Opening of the Far West 1840–90. By IRVING STONE. 1956. Pp. 459..... 5.95

Quest for a Continent. By WALTER SULLIVAN. Pp. 372..... 5.50

Man's Role in Changing the Face of the Earth. Ed. by WM. L. THOMAS. 1956. Pp. 1193. Illus... 12.50

Man's Emerging Mind. By N. J. BERRILL. 1955. Pp. 308..... 4.00

Conversation with the Earth. By HANS CLOOS. 1953. Pp. 413. Pls. 53. Tables 26..... 5.75

Man, Time and Fossils. By RUTH MOORE. 1953. Pp. 411, figs. 71, pls. 62..... 5.75

The Prehistoric Cultures of the Horn of Africa. By J. DESMOND CLARK. 1954. Pp. 385. Figs. 35. Pls. 52..... 18.50

Man and His Physical Universe. By RICHARD WISTAR. 1953. Pp. 488. Illus. 300..... 4.75

The Philosophy of Science (the link between science—philosophy). By PHILIPP FRANK. 1957. Pp. 394..... 7.65

Psychical Physics. By S. W. TROMP. 1949. Pp. 534. Illus. 153..... 8.00

Guide to Geologic Literature. By RICHARD M. PEARL. 1951. Pp. 239..... 5.50

Fundamentals of Earth Science. By HENRK D. THOMPSON. 1947. Pp. 420..... 4.00

The Earth We Live On. By RUTH MOORE. 1956. Pp. 416..... 6.00

Down to Earth, a Practical Guide to Archaeology. By ROBIN PLACE. Pp. 173. Figs. 88..... 7.50

The Earth Beneath Us. By H. H. SWINNERTON. 1956. Pp. 335..... 5.00

Geology and Ourselves. By F. H. EDMUNDS. 1956. Pp. 256. Pls. 12. Line drawings 15..... 10.00

Readings in Anthropology. E. ADAMSON HOEBEL, JESSE D. JENNINGS, and ELMER R. SMITH. 1955. Pp. 417..... 5.00

Symphony of the Earth. By J. H. F. UMBGROVE. 1951. Pp. 220. Pls. 10. Figs. 123..... 5.00

Readings in the Physical Sciences. By HARLOW SHAPLEY (ed.). 1948. Pp. 501..... 3.00

The Sea Around Us. By R. L. CARSON. 1951. Pp. 230. Figs. 4. Chart 1..... 3.50

This Great and Wide Sea. Rev. Ed. By R. E. COKER. 1949. Pp. 344. Pl. 91. Figs. 23..... 6.00

Volcanoes Declare War. By THOMAS A. JAGGAR. 1945. Pp. 166. Pl. 32. Figs. 34..... 4.85

Volcanoes New and Old. By MRS. SATIS N. COLEMAN. 1946. Pp. 234..... 4.75

Rocks and Rivers of North America. By ELLIS W. SHULER. 1945. Pp. 300..... 4.00

Engineering in History. By RICHARD S. KRIBY, SIDNEY WITHINGTON, ARTHUR B. DARLING, FREDERICK G. KILGOUR. 1956. Pp. 530..... 8.50

The Caves Beyond: The Story of the Floyd Collins' Crystal Expedition. By JOE LAWRENCE, JR., and ROGER W. BRUCKER. 1955. Pp. 283. Illus..... 4.75

The Earth and the Stars. 2nd Ed. By C. G. ABBOTT. 1946. Pp. 288. Illus..... 5.50

This Earth of Ours—Past and Present. By CALEB W. WOLFE. 1950. Pp. 384. Illus..... 5.00

The Face of the Moon. By R. B. BALDWIN. 1949. Pp. 226. Illus..... 5.00

Relativity for the Layman. By JAMES A. COLEMAN. 1954. Pp. 131. Figs. 24..... 2.75

Measuring Our Universe. By O. J. LEE. 1950. Pp. 170. Illus. 45..... 3.25

The Religion of the Modern Scientist. By DR. S. W. TROMP. 1951. Pp. 480. Illus. 113. Tables 3 5.50

Writing Useful Reports. Principles and Applications. By ROBERT E. TUTTLE and C. A. BROWN. 1956. Pp. 635..... 4.50

Writing the Technical Report. 3rd Ed. By J. R. NELSON. 1952. Pp. 388..... 4.50

French Bibliographic Digest: Science, Geology (2). Bibliographical Digest of French geological books and articles published from 1948 to 1954. Pp. 102 (The Cultural Division of the French Embassy, 972 Fifth Avenue, New York 21, N. Y. free of charge)..... 0.00

Address ECONOMIC GEOLOGY, Urbana, Ill. Books not in this list (except the publications of official Surveys and those of the Geological Society of America) will be furnished at Publisher's prices. Also consult more extended lists in volume 50.

Economic Geology Publishing Company will also attempt to secure past volumes of domestic and foreign geological journals and similar publications when contained in our file listings of secondhand book dealers. Special correspondence in search of material however can not be undertaken.